(Long-Baseline)
Interferometric Measurements of Binary Stars

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Outline

- **Introduction:**
  - Why study binary stars (with an interferometer)...
  - What kinds of binary star measurements are interesting
  - What kinds of binary stars are best suited to interferometry

- **History of Interferometric Binary Star Measurements:**
  - Classical imaging
  - Speckle
  - Long-baseline interferometry

- **How Do Interferometers Measure Binary Stars**
  - Visibility model
  - Interpretation

- **Case Study: HD 195987**
  - Why is the system interesting
  - Measurements & integrated orbit modeling

- **Future Directions**
Why Study Binary Stars?

Don’t try to teach a pig to sing…it doesn’t work, and it annoys the pig!

- Multiplicity (binary) is a pervasive phenomenon
  - Multiplicity’s role in the star formation process
    - Most stars form in multiple associations
  - Multiplicity’s role in the field
    - Two out of three solar-like stars have a stellar companion (DM91)
  - Multiplicity’s role in stellar evolution
    - The cornucopia of interacting binary stars

- Binary star interactions are SIMPLE, allowing insight into the properties of the components
  - Mass (through physical orbit)
  - Radius
  - Luminosity (through photometry, physical & angular orbit)
The Lexicon of Binary Stars

- **Eclipsing Binaries**
  - Systems aligned so that components occlude each other (constrains inclination)
  - (By phase-space arguments) highly likely to be close => short-period

- **Spectroscopic Binaries**
  - Systems whose kinematics and component properties yield detectable component radial velocity variations
  - SB1 – single-lined binaries
  - SB2 – double-lined binaries
  - Most (almost all) eclipsing binaries are spectroscopic binaries
    - Combination directly yields masses, radii

- **Visual Binaries**
  - Systems whose components can be resolved into two distinct sources…
    - …Allowing astrometry
    - Motion in time yields orientation of orbit (inclination)
    - Combined with SB2 => masses, distance (luminosity)
What Kinds of Binary Information is Interesting?

- Multiplicity statistics
- Orbit characteristics statistics
  
  as remnants of the formation process
- Component properties
  - Mass, Radius, Luminosity (the “big” three)
  - Abundance
    
    as constraints on stellar astrophysics & measure of system age
  - Rotation
    
    as markers of tidal interaction & internal convective structure
- Distance (“orbital parallax”)
  
  for direct & indirect luminosity calibration
What Kinds of Binary Measurements are Interesting?

- **Photometry**
  - Detection and measurements of binary eclipses
  - Marker of stellar rotation period
  - System and/or component luminosity

- **“Imaging”**
  - Inference of association
  - Astrometry
    - “Absolute” (relative to some “quasi-inertial” fiducials)
    - “Relative” (two components relative to each other)

- **Spectroscopy**
  - Astrophysics of components
  - “Velocimetry” – gauging the line-of-sight motions of components
What Binaries are Suitable for Interferometry Study?

- Interferometers are made for high-angular resolution applications—so the answer is obvious...
- Small-angular scale (how small?)
- Short period and/or distant (how short, how distant?)

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![Graph showing angular separation vs. period](image)

- Angular Separation (arcsec):
  - $M = 1.6 M_{\odot}$
  - $D = 400 \text{ pc}$

- Period (day):
  - $1 \text{ mas}$
  - $40 \text{ mas}$
  - $1.5 \text{ arcsec}$
Known Spectroscopic Binary Distributions

From Taylor, Harvin, and McAlister 2003

Log Greater Nodal Sep (mas)

Log Period (d)
“The Deal” with Binary Star Studies

- In (essentially) all cases, observational objective is to determine “physical orbit” (physical dimensions, orientation), this provides component masses.
- Eclipsing systems provide that with spectroscopy (“spectroscopic orbit”) & photometry (inclination).
- Non-eclipsing systems require integrating the “visual orbit” to determine system orientation.
- Ratio of physical and angular scales (e.g. semi-major axis) yields system distance (duh).

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MSS -- A
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➢ Why?
Describing Binary Systems

- (By definition) binary systems have *Primary* (A) and *Secondary* (B) components
- We describe binary kinematics with *orbital elements*
  - Four elements \((a, e, P, T_0)\) describe motion in the orbital plane
  - Three elements (Euler angles, \(i, \Omega, \omega\)) define orbital plane orientation
  - Three elements \((K_A, K_B, \gamma)\) describe rates projected onto the line-of-sight
- Additional parameters may describe component properties
  - Diameters \((\theta_A, \theta_B)\)
  - Intensity ratio \((r = B / A)\)
Historical Binary Studies

- Classical imaging/
- Speckle
- Long-baseline interferometry
  - Capella with Mt Wilson
  - $\alpha$ Vir with intensity interferometers
  - Mark III
  - HST FGS
  - NPOI
  - PTI
  - SUSY
The orbit of β Centauri determined from SUSI observations

Period: $357.0\pm0.3$ days
Inclination: $67.5\pm0.4$ deg
Semi-major axis: $25.3\pm0.2$ mas

Courtesy J. Davis
Admonitions From P. Tuthill

- Imaging may well be the “Holy Grail”, but the distinction between imaging and modeling is sometimes unclear.

- In all cases, you want to make optimal use of your data.

- Usually this means working “as close to your data” as possible.
Long-Baseline Interferometry Observables

- (L-B) Interferometers provide visual (i.e. astrometric) information on binary stars
- Interferometric visibility as proxy for relative component astrometry

\[
V_{\text{binary}} = \frac{P_A V_A + P_B V_B}{P_A + P_B} = e^{-2\pi i (u\alpha_1 + v\beta_1)} \left| V_A \right| + r \left| V_B \right| e^{-2\pi i (u\Delta\alpha + v\Delta\beta)} \left( 1 + r \right)
\]

\[
V_{\text{binary}}^2 = V_{\text{binary}}^* V_{\text{binary}} = \left| V_A \right|^2 + r^2 \left| V_B \right|^2 + 2r \left| V_A \right| \left| V_B \right| \cos(2\pi (u\Delta\alpha + v\Delta\beta)) \left( 1 + r \right)^2
\]

\[
= \left| V_A \right|^2 + r^2 \left| V_B \right|^2 + 2r \left| V_A \right| \left| V_B \right| \cos\left( \frac{2\pi}{\lambda} B \cdot \Delta s \right) \left( 1 + r \right)^2
\]

**\Delta s** – relative separation  
**r** – relative intensity  
**\( B \)** – baseline

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Separation Vector Modeling

Projected baseline motion (earth rotation) varies relative geometry

This geometry variation allows (straightforward!) estimation of binary separation
Examples of SUSI
Observations of β Centauri

10 May 1997: 5 metres

9 June 1998: 10 metres

11 April 1999: 15 metres

23 April 1999: 5 metres

Courtesy J. Davis
Integrated Modeling I

- Separation vector modeling works in many cases, but breaks down when:
  - System is marginally resolved, providing little visibility evolution on a given night
  - Few data points are available on given night
  - System moves appreciably during night
- Solution: integrated modeling – estimating orbit directly from visibilities (just like RV Orbit modeling)
- This is what (essentially) everyone in the business does

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Boden et al 1999
Integrated Modeling II

- While you’re at it, you might as well also directly integrate with RV measurements

Boden & Lane 2000
Case Study: HD 195987

- HD 195987 is a modestly low-metallicity ([Fe/H] ~ -0.5) double-lined spectroscopic binary (SB2)
- (Essentially) no eclipsing system constraints for metal-poor stellar models
- RV Orbit determine as part of Carney-Latham high-proper-motion survey
- Long-term velocity monitoring CfA
- Visibility orbit from PTI circa 1999
- Integrated orbit solution (Torres et al 2002)
- First (precision) O/IR interferometric solution for “metallicly-challenged” system
HD 195987 RV Orbit

- Modest eccentricity $(e \sim 0.3)$ double-lined orbit
- 0.1 contrast ratio in the visible – TODCOR extraction of RV lines
- 73 double-lined measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$ (d)</td>
<td>$49404.825 \pm 0.045$</td>
</tr>
<tr>
<td>$e$</td>
<td>$0.3103 \pm 0.0018$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$-5.867 \pm 0.038$</td>
</tr>
<tr>
<td>$K_A$</td>
<td>$28.944 \pm 0.046$</td>
</tr>
<tr>
<td>$K_B$</td>
<td>$36.73 \pm 0.21$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$357.03 \pm 0.35$</td>
</tr>
</tbody>
</table>
HD 195987 Visual Orbit

- a” ~ 15 mas; easily resolvable with PTI
- K-band operation facilitates measurement of secondary (r ~ 0.38)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (d)</td>
<td>57.3298 ± 0.0035</td>
</tr>
<tr>
<td>T0</td>
<td>51354.000 ± 0.069</td>
</tr>
<tr>
<td>e</td>
<td>0.30740 ± 0.00067</td>
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<tr>
<td>a</td>
<td>15.368 ± 0.028</td>
</tr>
<tr>
<td>i</td>
<td>99.379 ± 0.088</td>
</tr>
<tr>
<td>Ω</td>
<td>335.061 ± 0.082</td>
</tr>
<tr>
<td>ω</td>
<td>358.89 ± 0.53</td>
</tr>
</tbody>
</table>

Components rendered 3x actual size
HD 195987 Physical Orbit

- Simultaneous solution to both RV and PTI visibility data
- Complementary information about “mutual” elements (P, T₀, e, ω)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>P</td>
<td>57.32178 ± 0.00029</td>
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<tr>
<td>T₀</td>
<td>51353.813 ± 0.038</td>
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<tr>
<td>γ</td>
<td>-5.841 ± 0.037</td>
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<tr>
<td>KA</td>
<td>28.929 ± 0.046</td>
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<tr>
<td>KB</td>
<td>36.72 ± 0.21</td>
</tr>
<tr>
<td>a</td>
<td>15.378 ± 0.027</td>
</tr>
<tr>
<td>e</td>
<td>0.30626 ± 0.00057</td>
</tr>
<tr>
<td>i</td>
<td>99.364 ± 0.080</td>
</tr>
<tr>
<td>Ω</td>
<td>334.960 ± 0.070</td>
</tr>
<tr>
<td>ω</td>
<td>357.40 ± 0.29</td>
</tr>
</tbody>
</table>
### HD 195987 System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (M)</td>
<td>0.844 ± 0.018</td>
<td>0.6650 ± 0.0079</td>
</tr>
<tr>
<td>Teff (K)</td>
<td>5200 ± 100</td>
<td>4200 ± 200</td>
</tr>
<tr>
<td>oPlx (mas)</td>
<td>46.08 ± 0.27</td>
<td></td>
</tr>
<tr>
<td>Dist (pc)</td>
<td>21.70 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>MV (mag)</td>
<td>5.511 ± 0.028</td>
<td>7.91 ± 0.19</td>
</tr>
<tr>
<td>MH (mag)</td>
<td>3.679 ± 0.037</td>
<td>4.835 ± 0.059</td>
</tr>
<tr>
<td>MK (mag)</td>
<td>3.646 ± 0.033</td>
<td>4.702 ± 0.034</td>
</tr>
<tr>
<td>V-K (mag)</td>
<td>1.865 ± 0.039</td>
<td>3.21 ± 0.19</td>
</tr>
</tbody>
</table>

- 2% Primary Mass, 1% Secondary Mass
- Factor of two better than Hipparcos
Stellar Model Comparisons

- Having determined component parameters, it’s time to test stellar models!

- No single set of models do a perfect job of predicting HD195987 component parameters

- This is how an observationalist defines progress…
Future Directions

- We’ve been doing this binary thing for a while, what is there left to do?
  - Component parameters for stars that are not well covered by eclipsing systems
    - Subgiant & Giant stars
    - Pre-main sequence stars
    - Metal-poor & metal-rich stars
  - Systems where there’s “extra” physics
    - Tidal interaction & angular momentum evolution
    - Interacting systems
    - Higher-order (hierarchical) systems
  - Systems where there is science beyond/in addition to the component properties
    - e.g. Cluster distances and ages
Evolved Stars

- Surprisingly few high-precision tests exist of stars off the main sequence…
  - 12 Boo
  - Omi Leo
- But some more are on the way…
Short Period Systems: Tidal Interactions

Fig. 5. Diagram eccentricity versus period for the complete nearby G-dwarf sample. Note the strong circularization effect due to tidal stresses for short periods binaries. The symbols are according to the multiplicity of the system: ● double, △ triple, □ quadruple.
Hierarchical Systems

- \( \eta \) Vir was a known triple system recently done by NPOI (Hummel et al 2003)
- Non-coplanarity of outer and inner orbits established (diff 5.1 +/- 1.0 deg)
Summary (what to take away…)

- Binaries are important systems to study
  - “The hydrogen atoms of stellar astrophysics” argument
- LB Interferometers have an important role to play in binary star studies:
  - Making “visual” binaries out of “spectroscopic” ones
  - Resolving more distant systems
  - “Competitive” accuracy with eclipsing systems
  - Providing angular scale (distance!) for eclipsing systems
  - Providing additional component diversity beyond eclipsing systems
- LB Interferometers can also provide new windows into physics beyond component parameters
  - Tidal interactions
  - “Yardsticks and chronometers”
- All interferometers should study binary stars
  - (…to the exclusion of all other science…)
- Enjoy BC…