Resolved BD Companions: Combining Gaia and Direct Imaging

G. Mirek Brandt
Sagan Workshop 2022
Outline

- Importance of Brown Dwarfs (BDs)
- Tools to derive masses
- Understanding 1d measurements from Gaia/Hipparcos.
- Fitting orbits/masses to 1d measurements.
Based on work by

Yiting Li, Tim Brandt, Daniel Michalik, Minghan Chen, Trent Dupuy, Brendan Bowler, Thayne Currie, and many others...

On systems such as HR 8799, beta pic, Gl 229, Gl 758, 51 Eri, and more!

Precise Dynamical Masses and Orbital Fits for $\beta$ Pic b and $\beta$ Pic c
G. Mirek Brandt$^{4,1}$, Timothy D. Brandt$^1$, Trent J. Dupuy$^2$, Yiting Li$^1$, and Daniel Michalik$^{3,1}$

Improved Dynamical Masses for Six Brown Dwarf Companions Using Hipparcos and Gaia EDR3
G. Mirek Brandt$^{9,1}$, Trent J. Dupuy$^2$, Yiting Li$^1$, Minghan Chen$^1$, Timothy D. Brandt$^1$, Tin Long Sunny Wong$^1$, Thayne Currie$^{3,4}$, Brendan P. Bowler$^6$, Michael C. Liu$^7$, William M. J. Best$^9$, and Mark W. Phillips$^8$

Limits on the mass and initial entropy of 51 Eri b from Gaia EDR3 astrometry
Trent J Dupuy✉, G Mirek Brandt, Timothy D Brandt
Brown Dwarfs bridge the gap between planet & star formation.

Brown Dwarfs

~13x to 80x Jupiter’s mass

Planets & Exoplanets

Up to ~13x Jupiter’s mass

Stars

(Fueled by Nuclear Fusion)

Over ~80x Jupiter’s mass

credit: NASA/ Caltech/ R. Hurt (IPAC).
The masses of BD’s and Giant Planets are key

An *independently* measured mass can tell us

- 1. How old the companion is *and*
- 2. How the companion formed* and/or which model(s) it matches

* E.g., differences between cold/hot starts, e.g., Marleau, G. -D. ; Cumming, A. 2014 , or application to Beta pic b/c (Nowak et al. 2020, A&A 642)
The age and mass of the innermost HR 8799 planet

The First Dynamical Mass Measurement in the HR 8799 System

G. Mirek Brandt\textsuperscript{7,1}, Timothy D. Brandt\textsuperscript{1}, Trent J. Dupuy\textsuperscript{2}, Daniel Michalik\textsuperscript{3}, and Gabriel-Dominique Marleau\textsuperscript{4,5,6}

HR 8799 e

NRC-HIA, C. Marois, and Keck Observatory
The planet’s age from its mass!
The HR 8799 work was a result of coupling HTOF with REBOUND.

htof: A New Open-source Tool for Analyzing Hipparcos, Gaia, and Future Astrometric Missions

G. Mirek Brandt5,1, Daniel Michalik6,2, Timothy D. Brandt1, Yiting Li1, Trent J. Dupuy3, and Yunlin Zeng1,4
HTOF: all things absolute astrometry

[GitHub Link]

- Automatic downloading of Hip1 and Hip2, Gaia raw data for on-sky positions (a.k.a the intermediate astrometry; IAD).
- Easy parsing of the IAD files/scanning law
- Fit 5,7,9 parameter skypaths, compute hip2 error inflations etc..

HTOF: M Brandt. et al. 2021, arxiv: 2109.06761   (developed by myself, Daniel Michalik, Tim Brandt & Gavin K. Hung)
REBOUND: Rein & Liu 2012, github.com/hannorein/rebound
Open-source software framework for masses+orbits

Orvara combines absolute astrometry with relative astrometry (also RVs and relative RVs).

orvara: An Efficient Code to Fit Orbits Using Radial Velocity, Absolute, and/or Relative Astrometry

Timothy D. Brandt\textsuperscript{1} \textsuperscript{id}, Trent J. Dupuy\textsuperscript{2} \textsuperscript{id}, Yiting Li\textsuperscript{1} \textsuperscript{id}, G. Mirek Brandt\textsuperscript{7,1} \textsuperscript{id}, Yunlin Zeng\textsuperscript{3} \textsuperscript{id}, Daniel Michalik\textsuperscript{4} \textsuperscript{id}, Daniella C. Bardalez Gagliuffi\textsuperscript{5} \textsuperscript{id}, and Virginia Raposo-Pulido\textsuperscript{6} \textsuperscript{id}
Open-source software framework for masses+orbits

Orvara combines absolute astrometry with relative astrometry (also RVs and relative RVs).

orvara: An Efficient Code to Fit Orbits Using Radial Velocity, Absolute, and/or Relative Astrometry

Timothy D. Brandt¹ ID, Trent J. Dupuy² ID, Yiting Li¹ ID, G. Mirek Brandt⁷ ID, Yunlin Zeng³ ID, Daniel Michalik⁴ ID, Daniella C. Bardalez Gagliuffi⁵ ID, and Virginia Raposo-Pulido⁶ ID
A fantastic example of constraining detailed attributes of Brown Dwarfs, not just the age

€ Ind Ba+Bb
Empirically testing BD Model Isochrones

Using orvara !  Minghan Chen + Yiting Li et al. 2022, arxiv: 2205.08077
The common denominator of both examples: Relative astrometry + absolute astrometry to arrive at the mass. No radial velocities were used in either case!
Masses give us so much!
But we have *so few* of them...

<table>
<thead>
<tr>
<th>All known exoplanets</th>
<th>Brown Dwarfs (defined here as mass &gt; 13 Mjup)</th>
<th>Imaged Brown Dwarfs with known mass*</th>
</tr>
</thead>
<tbody>
<tr>
<td>About 5000</td>
<td>About 100</td>
<td>About 20</td>
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*meaning the mass is independently measured, not inferred from a cooling model.
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About 5000

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*meaning the mass is independently measured, not inferred from a cooling model.

We need to build up this sample size!
How to measure more masses
Combine relative astrometry + absolute astrometry (and RVs too).

For absolute astrometry: The standard is to use proper motion anomalies.

But with Gaia DR4 we will have the individual position measurements on-sky. (often called the epoch astrometry; or IAD for Hipparcos)
Relative motion

Absolute motion from Epoch Astrometry

+ 

= the mass (and other orbital elements)
Stars without heavy companions follow a linear path**

** after removing parallax motion
Let’s imagine a fictitious heavy companion around Barnard’s star.
A star + planet in their own frame of reference

(note that the “planet” mass is exaggerated, just to make the effect more obvious)
From our Earthly frame of reference.

Note: no parallax effect here.
But we cannot see the planet, so:
How do we solve for the mass?

if we have direct imaging over a long enough baseline, we already have strong constraints on:

- the eccentricity $e$
- the inclination $i$
- the semi-major axis

We can combine those with absolute astrometry to get the mass.
"Planet" mass = 0 Jupiter masses

Fixed period, fixed e (known from direct imaging)
For a face-on circular orbit, the host star will exhibit sky-plane motion with an amplitude of

$$\text{astrometric semi-amplitude} = \varpi \left( \frac{M_{\text{planet}}}{M_{\text{planet}} + M_{\text{star}}} \right) \left( \frac{a}{\text{A.U.}} \right)$$
But using the on-sky positions can be tricky.

These 2d measurements were not exactly like real Gaia observations...
Why one should interpret Hipparcos/Gaia on-sky positions carefully

For some systems, we know the companion orbits so well* that we can predict what Gaia DR3 would have reported for accelerations.

* from orvara fits to RV + proper motion anomalies + direct imaging (e.g, Y.Li + ‘21, Brandt+21, Qier An et al. ‘22)
Two examples from Qier An et al. (2022, in prep)

<table>
<thead>
<tr>
<th>Gaia DR3 accel_ra</th>
<th>accel_ra prediction (i.e., ground truth)</th>
<th>Gaussian sigma discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.8 ± 0.3 mas/yr²</td>
<td>12.7 ± 0.2 mas/yr²</td>
<td>14σ</td>
</tr>
<tr>
<td>-1.0 ± 0.1 mas/yr²</td>
<td>-1.6 ± 0.1 mas/yr²</td>
<td>4σ</td>
</tr>
</tbody>
</table>
Complications with real Gaia/Hipparcos

- 1-dimensional measurements.
- Potential systematics in the raw positions
Simple example

skypath with proper motion + orbital motion from an unseen companion.

No parallax motion.
2d measurements

\[(t_3, RA_3, DEC_3)\]

\[(t_0, RA_0, DEC_0)\]
Gaia/Hipparcos: One axis has *much larger* uncertainty → “1d measurement”
The star at time $t_i$ lay somewhere along the AC line, that is all you know.

Rotating scan angles $\theta$. 

**Showing Across-Scan (AC) only**
Fitting orbits to epoch astrometry

You can have multiple solutions that fit the data nearly equally as well but have very different orbital parameters.

To help illustrate that, next is an over-exaggerated example.
Is the gray orbit an OK fit to the data too?

\[ e = 0.7, T = 2\text{yr} \]

\[ e = 0.4, T = 3\text{yr} \]

\[ e = 0.7, T = 2\text{yr} \]
Both orbits give the same projected positions! (at the sampled times)
So two **very different** orbits can fit a single absolute astrometric path. The last example was contrived but..
In the hands-on session today

You’ll generate real examples of families of modestly different orbits that all fit simulated Gaia epoch astrometry.

Confidence intervals on e&T in these cases are difficult to define.
The complications

- 1-dimensional measurements.
- Potential systematics in the raw positions

Look out for G.M. Brandt et al. 2022 – discussion of systematics in Hipparcos epoch astrometry in great detail.
The big takeaways

- direct imaging + absolute astrometry (+ RVs) is powerful & now is a golden age of open-source software (e.g., htof, orvara, orbitize*)

- Orbit fitting to absolute astrometry 1d scans can be tricky.

Thank you!

Questions?

“An oil painting of the telescopes atop Maunakea”, created by the DallE neural net