Cooler than Gaia: Parallaxes of Ultracool Objects with WISE

Christopher A. Theissen
UC San Diego
May 23, 2018
Cooler than Gaia: Parallaxes of Ultracool Objects with WISE

Now with Gaia DR2!
The apparent paths of three stars across the sky during the three years of the Hipparcos mission. Each looping line shows the combination of parallax (an ellipse) and proper motion (a straight line) that best fits the data. The star's measured positions are shown by T-like intersections; these are often hidden under the dots, which mark their best-fit places on the line. Each curlicue in the 118,000-star database is different. From the Hipparcos Intermediate Data Web page.
Parallaxes

The apparent paths of three stars across the sky during the three years of the Hipparcos mission. Each looping line shows the combination of parallax (an ellipse) and proper motion (a straight line) that best fits the data. The star's measured positions are shown by T-like intersections; these are often hidden under the dots, which mark their best-fit places on the line. Each curlicue in the 118,000-star database is different. From the Hipparcos Intermediate Data Web page.

ESA/Hipparcos
The apparent paths of three stars across the sky during the three years of the Hipparcos mission. Each looping line shows the combination of parallax (an ellipse) and proper motion (a straight line) that best fits the data. The star’s measured positions are shown by T-like intersections; these are often hidden under the dots, which mark their best-fit places on the line. Each curlicue in the 118,000-star database is different. From the Hipparcos Intermediate Data Web page.
Parallaxes - Distance Ladder
Parallaxes - Distance Ladder

- Accurate distance to an important calibrator

Melis et al. (2014)
Dehnen & Binnen (1998)
Parallaxes - Kinematic Associations

Grouping in distance

Convergent point kinematics

Grouping in 3D space

Malo et al. (2013)
Parallaxes - Luminosity/Mass Function

Cruz et al. (2007)
Parallaxes - Luminosity/Mass Function

\[ \frac{dN}{dM} \propto M^{-\alpha} \]

Kirkpatrick et al. (2012)

Temperature

\[ \Phi(M_J) \times 10^{-3} \text{ objects pc}^{-3} \text{ mag}^{-1} \]

Cruz et al. (2007)
Gaia will save us all!

This table is breaking my brain.

<table>
<thead>
<tr>
<th>Source Type</th>
<th># sources in Gaia DR2</th>
<th># sources in Gaia DR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of sources</td>
<td>&gt; 1,500,000,000</td>
<td>1,142,679,769</td>
</tr>
<tr>
<td>Number of 5-parameter sources</td>
<td>&gt; 1,300,000,000</td>
<td>2,057,059</td>
</tr>
<tr>
<td>Number of 2-parameter sources</td>
<td>&gt; 200,000,000</td>
<td>1,140,622,719</td>
</tr>
<tr>
<td>Sources with mean G magnitude</td>
<td>&gt; 1,500,000,000</td>
<td>1,142,679,769</td>
</tr>
<tr>
<td>Sources with three-band photometry (G, Gp, Gpi)</td>
<td>&gt; 1,100,000,000</td>
<td>-</td>
</tr>
<tr>
<td>Sources with radial velocities</td>
<td>&gt; 6,000,000</td>
<td>-</td>
</tr>
<tr>
<td>Lightcurves for variable sources</td>
<td>&gt; 500,000</td>
<td>3,194</td>
</tr>
<tr>
<td>Known asteroids with epoch data</td>
<td>&gt; 13,000</td>
<td>-</td>
</tr>
<tr>
<td>Additional astrophysical parameters</td>
<td>&gt; 150,000,000</td>
<td>-</td>
</tr>
</tbody>
</table>

Adrian Price-Whelan @adrianprw · Mar 18
during a great Sunday phone chat with @davidwhogg, we noted that after >5 years of "preparing" for @ESAGaia DR2, we're not even emotionally prepared for the fact that we're still not prepared for DR2 -- omg April is going to be fun.

David W. Hogg @davidwhogg · Mar 23
I am so zen about @ESAGaia #GaiaMission #GaiaDR2 on April 25. We have a lifetime to figure it out!

Jackie Faherty @jfaherty · Apr 4
It is exactly three weeks until everything we know about the Milky Way will change and all we understand about stars will be updated. Are you ready for Gaia???? #GaiaDR2 @ESAGaia #gaiaday
Gaia will save us all!

David W. Hogg @davidwhogg · 12h
I'm going to want way more booze to CELEBRATE this week! #GaiaDR2

Jackie Faherty @jfaherty · Apr 18
Is the time of the Gaia DR2 data drop public yet????? Inquiring minds want to know! #waitingforGaia @ESAGaia

Jackie Faherty @jfaherty · 34m
People of twitter, there are two days left until all of stellar astrophysics, galactic kinematics and all things in between gets turned on its head by @ESAGaia #WaitingForGaia #yearofthemilkyway Get excited!!!!!!

David W. Hogg @davidwhogg · Mar 23
I am so zen about @ESAGaia #GaiaMission #GaiaDR2 on April 4 - a lifetime to figure it out!

Jackie Faherty @jfah @fahe
It is exactly three week change and all we understand is Gaia???? #GaiaDR2 @ESAGaia gaiaday
Gaia will save us all!

Adrian Price-Whelan @adri: during a great Sunday phone call with @ESAGaia - the fact that we're still not properly tracking Gaia????

David W. Hogg @davidwh: I am so zen about @ESAGaia... lifetime to figure it out!

Gaia Collaboration (2016)
“We want to emphasize that... Gaia DR1 cannot be considered as giving a final and definite answer on the so-called Pleiades distance discrepancy.” - Gaia Collab.
Gaia will save us all!

Gaia Collaboration (2016)
Gaia will save us all!… maybe

Gaia will be incomplete for nearby, ultracool objects

Theissen (2018)
The Wide-field Infrared Survey Explorer (WISE)

All-sky survey in 4 mid-infrared (MIR) bands (3.4, 4.6, 12, and 22 microns)
Is WISE better (than Gaia)?

- Ultracool objects produce very little flux at optical (Gaia) wavelengths.
- Flux increases at MIR wavelengths for the coolest objects.
Is *WISE* better (than *Gaia*)?

- Ultracool objects produce very little flux at optical (*Gaia*) wavelengths.
- Flux increases at MIR wavelengths for the coolest objects.
Is *WISE* better (than *Gaia*)?

- Ultracool objects produce very little flux at optical (*Gaia*) wavelengths.
- Flux increases at MIR wavelengths for the coolest objects.
WISE Survey Strategy

~90°
WISE Survey Strategy

\[ \sim 90^\circ \]
WISE Survey Strategy

Roughly every 6 months for 7 years
Measuring Parallaxes with WISE

K. L. Luhman
Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA; kluhman@astro.psu.edu
and
Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA

**Table 2**
Parallax, Proper Motion, and Photometry for WISE J104915.57−531906.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>π</td>
<td>0.496 ± 0.037″</td>
</tr>
<tr>
<td>μα cos δ</td>
<td>−2.759 ± 0.006″ yr⁻¹</td>
</tr>
<tr>
<td>μδ</td>
<td>+0.354 ± 0.006″ yr⁻¹</td>
</tr>
</tbody>
</table>

DSS IR (1978)  
DSS red (1992)  
DENIS J (1999)  
2MASS J (1999)  
WISE W1 (2010)  
GMOS i (2013)  

Luhman (2013)
Can we do better with just WISE?

- One WISE pixel is 2750 mas (2.75")
- We can get a relative uncertainty of ~10 mas (for bright sources)

Theissen (2018)
Can we do better with just *WISE*?

**Equations of Motion**

\[
(\alpha_i - \alpha_0) \cos \delta_0 = \Delta \alpha + \mu_\alpha (t_i - t_0) + \pi (P_{\alpha,i} - P_{\alpha,0}),
\]

\[
\delta_i - \delta_0 = \Delta \delta + \mu_\delta (t_i - t_0) + \pi (P_{\delta,i} - P_{\delta,0}),
\]
Can we do better with just *WISE*?

Plug into your favorite solver
(I prefer the *emcee*; Foreman-Mackey+ 2013)
Can we do better with just $WISE$?

Plug into your favorite solver
(I prefer the $emcee$; Foreman-Mackey+ 2013)
Yes we can!

Table 2
Parallax, Proper Motion, and Photometry for WISE J104915.57—531906.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0.496 ± 0.037″</td>
</tr>
<tr>
<td>$\mu_\alpha \cos \delta$</td>
<td>$-2.759 \pm 0.006″$ yr$^{-1}$</td>
</tr>
<tr>
<td>$\mu_\delta$</td>
<td>$+0.354 \pm 0.006″$ yr$^{-1}$</td>
</tr>
</tbody>
</table>

$\mu_\alpha \cos \delta$ at J2000.0 = $-2762.2 \pm 2.3$ mas yr$^{-1}$

$\mu_\delta$ at J2000.0 = 354.5 ± 2.8 mas yr$^{-1}$

$\pi$ at J2000.0 = 501.118 ± 0.093 mas
Yes we can!

**Table 2**
Parallax, Proper Motion, and Photometry for WISE J104915.57−531906.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0.496 ± 0.037″</td>
</tr>
<tr>
<td>$\mu_\alpha \cos \delta$</td>
<td>$-2.759 \pm 0.006''$ yr$^{-1}$</td>
</tr>
<tr>
<td>$\mu_\delta$</td>
<td>$+0.354 \pm 0.006''$ yr$^{-1}$</td>
</tr>
</tbody>
</table>

Luhman (2013)

HST!
known high-likelihood members of the ABDMG. The effective temperature of 2MASS J13243553+6358281 provides the first precise constraint on the L/T transition at a known young age and indicates that it happens at a temperature of \(\sim 1150\,\text{K}\) at \(\sim 150\,\text{Myr}\), compared to \(\sim 1250\,\text{K}\) for field brown dwarfs.
Some caveats - PSF dipole residuals

Presumably due to “PSF models adopted by the WISE team are not symmetric with respect to swapping the scan direction”

Meisner, Lang, & Schlegel (2018)
Correction for the PSF dipole residuals

Use reference objects close to the target object to correct for this shift (10’ x 10’ image)
Correction for the PSF dipole residuals

Correction applied to QSOs (bright, non-moving)

Theissen (2018)
Very important correction

Typical L7 field dwarf
Very important correction

Typical L7 field dwarf
Wait one second

- Possible low-gravity (young, overluminous) object
- Likely member of a young moving group.
Wait one second


MCMC Fit

\[ \Delta a \cos \delta = -23 \pm 6 \text{ mas yr}^{-1} \]
\[ \mu_\delta = -353 \pm 7 \text{ mas yr}^{-1} \]
\[ \pi = 64 \pm 14 \text{ mas} \]
What are the limits?

This method can, in principle, be used for objects out to \( \sim 25 \) pc.
What are the limits?

W2 = 10.86
Spectrophotometric distance = 15—24 pc
Gaia DR2 = 19.53 ± 0.55 pc (goodness of fit is baaaad)
What are the limits?

W2 = 9.98

Other trigonometric distances:
- URAT = 22.0 ± 2.8 pc
- Gaia DR2 = 27.62 ± 0.41 pc (goodness of fit is baaaad)
Overluminous Binaries

Unresolved binaries appear overluminous (highly dependent on flux ratio)
Overluminous Binaries

Unresolved binaries appear overluminous (highly dependent on flux ratio)
Or...low surface gravity

Young, low-gravity objects are also overluminous

Faherty+ (2016)
Controversy?

Spectral type - Absolute magnitude diagram
Controversy?

Spectral type - Absolute magnitude diagram

Spectral binary: L8+T3.5 (Burgasser+ 2010)

Theissen (2018)
Controversy?

Spectral type - Absolute magnitude diagram

Spectral binary: L8+T3.5 (Burgasser et al. 2010)

Object appears to be more consistent with a single object (T2; Looper et al. 2007)
Future directions: unWISE for deeper photometry

Meisner, Lang, & Schlegel (2018)
Thanks for listening
### Gaia by the numbers

<table>
<thead>
<tr>
<th>Total number of sources</th>
<th># sources in Gaia DR2</th>
<th># sources in Gaia DR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of sources</td>
<td>1,692,919,135</td>
<td>1,142,679,769</td>
</tr>
<tr>
<td>Number of 5-parameter sources</td>
<td>1,331,909,727</td>
<td>2,057,050</td>
</tr>
<tr>
<td>Number of 2-parameter sources</td>
<td>361,009,408</td>
<td>1,140,622,719</td>
</tr>
<tr>
<td>Sources with mean G magnitude</td>
<td>1,692,919,135</td>
<td>1,142,679,769</td>
</tr>
<tr>
<td>Sources with mean G\textsubscript{BP}-band photometry</td>
<td>1,381,964,755</td>
<td>-</td>
</tr>
<tr>
<td>Sources with mean G\textsubscript{RP}-band photometry</td>
<td>1,383,551,713</td>
<td>-</td>
</tr>
<tr>
<td>Sources with radial velocities</td>
<td>7,224,631</td>
<td>-</td>
</tr>
<tr>
<td>Variable sources</td>
<td>550,737</td>
<td>3,194</td>
</tr>
<tr>
<td>Known asteroids with epoch data</td>
<td>14,099</td>
<td>-</td>
</tr>
<tr>
<td>Gaia-CRF sources</td>
<td>556,869</td>
<td>2,191</td>
</tr>
<tr>
<td>Effective temperatures (T\textsub{eff})</td>
<td>161,497,595</td>
<td>-</td>
</tr>
<tr>
<td>Extinction (A\textsub{G}) and reddening (E(G\textsub{BP}-G\textsub{RP}))</td>
<td>87,733,672</td>
<td>-</td>
</tr>
<tr>
<td>Sources with radius and luminosity</td>
<td>76,956,778</td>
<td>-</td>
</tr>
</tbody>
</table>