Radio astrometry to young stars in the Gaia era

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IRyA colloquium.
April 12th, 2018
Distances are **Fundamental** for everyone.

**Distance**
- Luminosity wrong by ~50%
- Density wrong by 25%
- Stellar Mass wrong by ~100%
- Velocity in the plane of the sky
- Physical size
Example: Kinematic Studies

- The distance to ONC is 388±5 pc (Kounkel et al. 2017).
- We could determine the tangential velocities.
- The bulk and dispersion velocities of the cluster.

Proper motions of 92 sources in the ONC by using ~10 VLA observations made on the last 30 years. (Dzib et al. 2017; Rodriguez, Dzib et al 2017).
$\mu_\alpha \cos \delta = 1.07 \pm 0.09 \text{ mas yr}^{-1}$, \\
$\mu_\delta = -0.84 \pm 0.16 \text{ mas yr}^{-1}$.

$1.18 \pm 0.24 \text{ km/s}$

Toward the galactic plane

$\sigma_\alpha = 1.08 \pm 0.07 \text{ mas yr}^{-1} \equiv 2.12 \pm 0.13 \text{ km s}^{-1}$, \\
$\sigma_\delta = 1.27 \pm 0.15 \text{ mas yr}^{-1} \equiv 2.49 \pm 0.29 \text{ km s}^{-1}$.

$\vec{r}_* \times \vec{\delta v}_* = 0.7 \pm 1.6 \text{ km s}^{-1}$, and \\
$\vec{r}_* \cdot \vec{\delta v}_* = -0.1 \pm 2.0 \text{ km s}^{-1}$. 
The central position is the center of the close approach of sources BN, I and n. (Dzib et al. 2017)
Trigonometric parallax

\[ d(\text{pc}) = \frac{1}{\pi(\text{''})} \]

e.g. For *proxima centauri* \( \pi = 0''\,77 \)
Trigonometric parallax

\[ \alpha(t) = \alpha_0 + \mu_\alpha t + \pi f_\alpha(t) \]

\[ \delta(t) = \delta_0 + \mu_\delta t + \pi f_\delta(t) \]
Distances to star forming regions

- Distances >100 pc ($\pi < 0''.01$).
  - Need high resolution observations.

- Highly obscured at optical wavelengths (Many of them won’t be detected by GAIA).
  - Observations at larger wavelengths.

- Old distances often assume properties of the stars.
  - Direct measurements.
The most precise method: Very Long Baseline Interferometry

- Resolution <0''.002 ~ 0.00005.
- Quasars used for phase reference.
- Can observe only sources with high brightness temperatures (>10^6 K).
How to choose a good target?

• With poor and/or controversial determined distance.

• Peculiar object (Highly studied).

• High brightness temperature:
  
  **Masers (BESSEL), Magnetically active young stars (GOBELINs), Wind collision regions (Dzib et al. 2013), etc.**
Masers

- Brightness temperatures (>10^{10} K).
- Methanol, SiO and Water maser associated with Young Stellar Objects.

The smallest trigonometrical parallax measured:
\[ \Pi = 0.049 \pm 0.006 \text{ mas} \]
\[ \Rightarrow d = 20.4 \pm 2.5 \text{ kpc} \]
(Sanna et al. 2017).

Image via Bill Saxton, NRAO/AUI/NSF; Robert Hurt, NASA.
Magnetically active young stars

- Girosynchrotron emission.
- Brightness temperatures (>10^6 K).
Magnetically active young stars

- Girosynchrotron emission.
- Brightness temperatures (>10^6 K).
Magnetically active young stars

- Girosynchrotron emission.
- Brightness temperatures ($>10^6$ K).

T Tau Sb (Taurus) at 142 ± 3 pc (Loinard et al. 2005)
## Main results from our group

<table>
<thead>
<tr>
<th>Complex</th>
<th>Subregion</th>
<th>$\pi$ (mas)</th>
<th>$D$ (pc)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiuchus</td>
<td>L1688 (Core)</td>
<td>$7.28 \pm 0.06$</td>
<td>$137.3 \pm 1.2$</td>
<td>Ortiz-Leon et al. (2017a)</td>
</tr>
<tr>
<td></td>
<td>L1689</td>
<td>$6.79 \pm 0.16$</td>
<td>$147.3 \pm 3.4$</td>
<td>Ortiz-Leon et al. (2017a)</td>
</tr>
<tr>
<td>Serpens</td>
<td>Main</td>
<td>$2.29 \pm 0.05$</td>
<td>$436 \pm 9.2$</td>
<td>Ortiz-Leon et al. (2017b), Dzib et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>W40</td>
<td>$2.29 \pm 0.05$</td>
<td>$436 \pm 9.2$</td>
<td>Ortiz-Leon et al. (2017b)</td>
</tr>
<tr>
<td>Orion</td>
<td>ONC</td>
<td>$2.58 \pm 0.03$</td>
<td>$388 \pm 5$</td>
<td>Kounkel et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>L1641</td>
<td>$2.34 \pm 0.05$</td>
<td>$428 \pm 10$</td>
<td>Kounkel et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>NGC 2068</td>
<td>$2.58 \pm 0.07$</td>
<td>$388 \pm 10$</td>
<td>Kounkel et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>NGC 2024</td>
<td>$2.36 \pm 0.06$</td>
<td>$423 \pm 15$</td>
<td>Kounkel et al. (2017)</td>
</tr>
<tr>
<td>Taurus</td>
<td>L1495</td>
<td>$7.72 \pm 0.02$</td>
<td>$129.5 \pm 0.3$</td>
<td>Galli et al. (submitted)</td>
</tr>
<tr>
<td></td>
<td>L1513, L1519</td>
<td>$7.01 \pm 0.11$</td>
<td>$143 \pm 2$</td>
<td>Galli et al. (submitted)</td>
</tr>
<tr>
<td></td>
<td>L1551</td>
<td>$6.79 \pm 0.03$</td>
<td>$147.3 \pm 0.5$</td>
<td>Galli et al. (submitted)</td>
</tr>
<tr>
<td></td>
<td>L1534</td>
<td>$7.30 \pm 0.13$</td>
<td>$137 \pm 3$</td>
<td>Galli et al. (submitted)</td>
</tr>
<tr>
<td>Perseus</td>
<td>IC348</td>
<td>$3.07 \pm 0.10$</td>
<td>$326 \pm 11$</td>
<td>Ortiz-Leon et al. (in prep)</td>
</tr>
<tr>
<td>Cepheus</td>
<td>Cep A</td>
<td>$1.43 \pm 0.06$</td>
<td>$700 \pm 30$</td>
<td>Dzib et al. (2011)</td>
</tr>
</tbody>
</table>

In this talk I will present three more cases.
The distance to IRAS 16293-2422
IRAS 16293-2422

- It is triple system with solar-mass protostars, very well studied.
- It has an age <10^5 years old.
- It is an important laboratory for molecules studies (e.g. Caux et al. 2011).
- It is thermal radio sources (e.g. Pech et al. 2010).
- It has associated water masers.
Imai et al. (2007) measured $178^{+18}_{-37}$ pc to the water masers associated to IRAS 16293-2422.

- Structure and fluxes are highly variable.
- They used masers with different radial velocities.
Loinard et al. (2008) measured the distance to two stars in the Ophiuchus core to be $120 \pm 4$ pc.

- Chini (1981) -> 165 pc
- De Geus et al. (1989) -> $125 \pm 25$ pc
- Knude & Hog (1998) -> 120 pc
- Lombardi et al. (2008) -> $119 \pm 6$ pc
- Mamajek (2007) -> 135 ± 8 pc

They are NOT direct measurements to IRAS 16293.
VLA survey to look for magnetically active stars

Location of YSOs (blue circles) and YSO candidates (green circles)
Image from Dzib et al. (2013).
Ortiz-Leon et al. (2017) show that L1689 is at $147 \pm 3$ pc and L1688 at $137.3 \pm 1.2$ pc.
One day in Mexico...

During EHT observations in the Large Millimeter Telescope.

Theorists view of what it should look like...
VLBA observations of water masers

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Date of observation (yyyy-mm-dd/hh:mm)</th>
<th>Synthesized beam (mas×mas); PA</th>
<th>Noise (mJy beam⁻¹)</th>
<th>Peak (Jy beam⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2005-Aug-02/03:00</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>B</td>
<td>2005-Aug-16/02:05</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>C</td>
<td>2005-Aug-30/01:10</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>D</td>
<td>2005-Sep-12/23:17</td>
<td>1.14×0.29; -20.1°</td>
<td>19</td>
<td>0.35</td>
</tr>
<tr>
<td>E</td>
<td>2005-Sep-25/22:19</td>
<td>0.74×0.25; -10.2°</td>
<td>10</td>
<td>0.21</td>
</tr>
<tr>
<td>F</td>
<td>2005-Oct-13/20:38</td>
<td>0.77×0.26; -10.9°</td>
<td>40</td>
<td>0.55</td>
</tr>
<tr>
<td>G</td>
<td>2005-Nov-01/19:55</td>
<td>0.91×0.29; -7.9°</td>
<td>40</td>
<td>2.23</td>
</tr>
<tr>
<td>H</td>
<td>2005-Nov-12/19:12</td>
<td>0.87×0.27; -11.6°</td>
<td>33</td>
<td>0.70</td>
</tr>
<tr>
<td>I</td>
<td>2005-Nov-27/18:14</td>
<td>0.84×0.25; -8.7°</td>
<td>38</td>
<td>0.53</td>
</tr>
<tr>
<td>J</td>
<td>2005-Dec-08/17:31</td>
<td>1.33×0.31; 7.2°</td>
<td>21</td>
<td>1.10</td>
</tr>
<tr>
<td>K</td>
<td>2005-Dec-22/16:34</td>
<td>0.83×0.26; -9.7°</td>
<td>18</td>
<td>0.56</td>
</tr>
<tr>
<td>L</td>
<td>2006-Jan-06/15:36</td>
<td>0.78×0.28; -8.9°</td>
<td>15</td>
<td>0.69</td>
</tr>
<tr>
<td>M</td>
<td>2006-Jan-18/14:53</td>
<td>0.74×0.25; -11.1°</td>
<td>33</td>
<td>0.83</td>
</tr>
<tr>
<td>N</td>
<td>2006-Feb-04/13:41</td>
<td>0.81×0.25; -11.0°</td>
<td>28</td>
<td>0.48</td>
</tr>
<tr>
<td>O</td>
<td>2006-Mar-02/12:00</td>
<td>0.93×0.30; -3.4°</td>
<td>20</td>
<td>0.46</td>
</tr>
<tr>
<td>P</td>
<td>2006-Mar-17/11:02</td>
<td>0.83×0.26; -8.6°</td>
<td>26</td>
<td>0.38</td>
</tr>
<tr>
<td>Q</td>
<td>2006-Mar-30/10:05</td>
<td>0.87×0.28; -7.0°</td>
<td>17</td>
<td>0.53</td>
</tr>
<tr>
<td>R</td>
<td>2006-Apr-13/09:07</td>
<td>0.78×0.26; -9.2°</td>
<td>30</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Images of channel 252 ($V_{lsr}$=6.1 km/s, peak of the emission).
Track spots.
This work

We can see the movement of the front shock.
### This work

<table>
<thead>
<tr>
<th>Fit</th>
<th>Spot</th>
<th>$\pi \pm \sigma_\pi$ (mas)</th>
<th>$d$ (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>$6.9 \pm 4.7$</td>
<td>$145^{+314}_{-59}$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$7.1 \pm 1.3$</td>
<td>$141^{+30}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>$8.3 \pm 2.1$</td>
<td>$120^{+40}_{-24}$</td>
</tr>
<tr>
<td>Simultaneous</td>
<td>2</td>
<td>$7.4 \pm 1.1$</td>
<td>$135^{+23}_{-16}$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This work

\[ \alpha_{\text{ICRF}} \left( ' \right) [\text{from } 16^h32^m] \]

\[ \delta_{\text{ICRF}} \left( '' \right) [\text{from } -24^h28'] \]

<table>
<thead>
<tr>
<th>With offset</th>
<th>1/2</th>
<th>7.1 ± 1.3</th>
<th>( 141^{+30}_{-21} )</th>
</tr>
</thead>
</table>

| Spots 1 & 2 | 1+2 | 7.1±0.5   | \( 141^{+10}_{-9} \) |
- Tracking the front shock in R. A.
- R.A. is most important for parallax determination (Reid et al. 2009).
Parallax sinusoid in the R.A. direction.

\[ D = 152 \pm 15 \text{ pc} \]
Table 5. Parameters obtained from the astrometric fits. The systematic errors that were added quadratically are also presented.

<table>
<thead>
<tr>
<th>Fit</th>
<th>Spot</th>
<th>$\pi \pm \sigma_\pi$ (mas)</th>
<th>$d$ (pc)</th>
<th>$\mu_\alpha \cos \delta \pm \sigma_{\mu_\alpha \cos \delta}$ (mas yr$^{-1}$)</th>
<th>$\mu_\delta \pm \sigma_{\mu_\delta}$ (mas yr$^{-1}$)</th>
<th>Offsets (mas)</th>
<th>Post-fit rms (mas)</th>
<th>Systematic Errors (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual</td>
<td>1</td>
<td>6.9 ± 4.7</td>
<td>145$^{+314}_{-39}$</td>
<td>$-44 \pm 19$</td>
<td>$-13 \pm 6$</td>
<td>...</td>
<td>...</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.1 ± 1.3</td>
<td>141$^{+30}_{-21}$</td>
<td>$-39 \pm 2$</td>
<td>$-16 \pm 5$</td>
<td>...</td>
<td>...</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8.3 ± 2.1</td>
<td>120$^{+40}_{-24}$</td>
<td>$-37 \pm 3$</td>
<td>$-21 \pm 4$</td>
<td>...</td>
<td>...</td>
<td>0.24</td>
</tr>
<tr>
<td>Simultaneous</td>
<td>1</td>
<td>7.4 ± 1.1</td>
<td>135$^{+23}_{-16}$</td>
<td>$-47 \pm 5$</td>
<td>$-13 \pm 6$</td>
<td>...</td>
<td>...</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.1 ± 1.3</td>
<td>141$^{+30}_{-21}$</td>
<td>$-38 \pm 3$</td>
<td>$-21 \pm 4$</td>
<td>...</td>
<td>...</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.1 ± 1.3</td>
<td>141$^{+30}_{-21}$</td>
<td>$-42 \pm 3$</td>
<td>$-13 \pm 8$</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.17</td>
</tr>
<tr>
<td>With offset</td>
<td>1</td>
<td>7.1 ± 0.5</td>
<td>141$^{+10}_{-9}$</td>
<td>$-36 \pm 2$</td>
<td>$-16 \pm 5$</td>
<td>$-0.4 \pm 1.0$</td>
<td>$1.4 \pm 2.3$</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.1 ± 0.5</td>
<td>141$^{+10}_{-9}$</td>
<td>$-39 \pm 2$</td>
<td>$-13 \pm 1$</td>
<td>...</td>
<td>...</td>
<td>0.29</td>
</tr>
<tr>
<td>Spots 1 &amp; 2</td>
<td>1+2</td>
<td>7.1 ± 0.5</td>
<td>141$^{+10}_{-9}$</td>
<td>$-36 \pm 2$</td>
<td>$-16 \pm 5$</td>
<td>$-0.4 \pm 1.0$</td>
<td>$1.4 \pm 2.3$</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Dzib et al. (2018)

$D = 141^{+30}_{-21}$ pc
A revised distance to IRAS 16293–2422 from VLBA astrometry of associated water masers

S. A. Dzib¹, G. N. Ortiz-León¹,², A. Hernández-Gómez³,⁴, L. Loinard³,⁵, A. J. Mioduszewski⁶, M. Claussen⁶, K. M. Menten¹, E. Caux⁴, and A. Sanna¹

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The distance to LkHa 101 cluster
LkHα 101 cluster

- The most massive member is LkHα 101, a young B star.
- Distance controversy (Andrews & Wolk 2008):
  - Herbig (1971) proposed 800 pc.
  - Still 700 pc is the most commonly used distance.
- It was not in Gaia DR1
- Radio is the only chance to measure the distance to stars in this cluster.
- No masers.
Magnetically active members

Osten & Wolk (2009)
Table 1. Observed sources. The names and infrared classes from Osten & Wolk (2009).

<table>
<thead>
<tr>
<th>Name</th>
<th>IR</th>
<th>Class</th>
<th>Detected?</th>
</tr>
</thead>
<tbody>
<tr>
<td>(LkHα 101 VLA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J043010.87+351922.4</td>
<td>III</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>J043016.04+351726.9</td>
<td>III</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>J043017.90+351510.0</td>
<td>...</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>J043019.14+351745.6</td>
<td>II</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>J042953.98+351848.2</td>
<td>III</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>J043001.15+351724.6</td>
<td>III</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>J043002.64+351514.9</td>
<td>II</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
\[ \alpha_{J2015.24} = 04^h 30^m 01.146538 \pm 0.000009 \]
\[ \delta_{J2015.24} = 35^\circ 17' 24''.4251 \pm 0''.0001 \]
\[ \mu_\alpha \cos \delta = 1.86 \pm 0.04 \text{ mas yr}^{-1} \]
\[ \mu_\delta = -5.70 \pm 0.05 \text{ mas yr}^{-1} \]
\[ \varpi = 1.87 \pm 0.10 \text{ mas}. \]

\[
\text{D} = 535 \pm 29 \text{ pc}
\]
VLBA DETERMINATION OF THE DISTANCE TO NEARBY STAR-FORMING REGIONS: VIII
THE LKHα 101 CLUSTER

SERGIO A. DZIB,1 GISELA N. ORTIZ-LEÓN,1,2 L. LOINARD,3,4 A. J. MIODUSZEWSKI,5 L. F. RODRÍGUEZ,3 S.-N. X. MEDINA,1 AND R. M. TORRES6

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6Centro Universitario de Tonalá, Universidad de Guadalajara, Avenida Nuevo Periférico No. 555, Ejido Dan José Tatepozco, C.P. 48525, Tonalá, Jalisco, México.
Conclusions

The distance to **LkHa 101** cluster is $535 \pm 29$ pc.

The distance to **IRAS 16293-2422** is $141 \pm 25$ pc in good agreement with the distance to magnetically active stars in L1689 and 25% more than the most used distance.

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700 pc Herbig et al. (2004)

600 pc Andrews & Wolk (2008)

535 ± 29 pc Dzib et al. (2018)

178 pc Imai et al. (2007)

147 pc Ortiz-Leon et al. (2017)

141 ± 25 pc Dzib et al. (in press)

120 pc Loinard et al. (2008)

Image Credit: Sac Medina
General Conclusions

• VLBI astrometry is the best tool to determine distances to highly obscured stars, and it has now provided new and more accurate results.

  Fundamental for accurate calculation of any OTHER physical parameter.

• It will also provide dynamical masses for several YSOs.
Determination of dynamical masses of binary stars.
Next Very Large project: Dynamical masses of YSOs from VLBA astrometry

Observations facilities:
• ~300 hours with VLBA in PRIORITY A.

Durations:
• Three years.

Goals:
• Observe binary stars to determine their masses.

Leadership:
– S.A. Dzib (PI),
– G. Ortiz-Leon (co-PI),
– L. Loinard (co-PI)
– GOBELINS team

Collaborators, students are very welcome!