Masers as Probes of Galactic Structure

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What does the Milky Way look like?

GAIA range ($\pm 10$ to $20 \mu$as); but cannot see through dust in Galactic plane

VLBI range ($\pm 5$ to $20 \mu$as): can “see” through plane to massive star forming regions that trace spiral structure
Very Long Baseline Interferometry: VLBA, VERA & EVN

- Radio waves “see” through galaxy
- Can “synthesize” telescope the size of the Earth

Fringe spacing (eg, VLBA):
\[ \theta_f \sim \frac{\lambda}{D} \sim 1 \text{ cm} / 8000 \text{ km} = 250 \mu\text{as} \]

Centroid Precision:
\[ 0.5 \theta_f / \text{SNR} \sim 10 \mu\text{as} \]

Systematics:
path length errors \sim 2 \text{ cm} (\sim 2 \lambda)
shift position by \sim 2\theta_f \sim 500 \mu\text{as}

Relative positions (to QSOs):
\[ \Delta \Theta \sim 1 \text{ deg} (0.02 \text{ rad}) \]
cancel systematics: \[ \Delta \Theta \ast 2\theta_f \sim 10 \mu\text{as} \]
Parallax Signatures

Projected Earth's Orbit

Proper Motion

North Offset (mas)

East Offset (mas)

Offset (mas)

Epoch (years)

2008 2009 2010

2008 2009 2010

Offset (mas)

-1 -0.5 0 0.5 1

-1 -0.5 0 0.5 1
Orion Nebular Cluster Parallax

VLBA: \( \Pi = 2.42 \pm 0.04 \) mas
D = 414 ± 7 pc

VERA: D = 419 ± 6 pc

Menten, Reid, Forbrich & Brunthaler (2007)
Mapping the Milky Way

6.7/12.2 GHz CH$_3$OH masers

22 GHz H$_2$O masers

VLBA Key Science Project: 5000 hours over 5 years to measure hundreds of parallaxes/proper motions

Observations for ~70 masers started 2010/2011 recently completed
Parallax for Sgr B2(Middle) H$_2$O masers

$\Pi = 129 \pm 12 \, \mu\text{as} \quad (D=7.8 \pm 0.8 \, \text{kpc})$
Parallax for W 49N H$_2$O masers

$\Pi = 82 \pm 6 \; \mu$as (D=12.2 $\pm$ 0.9 kpc)
Mapping Spiral Structure

• Preliminary results of parallaxes from VLBA, EVN & VERA:
  • Arms assigned by CO
  • Tracing most spiral arms
  • Inner, bar-region is complicated

Background: artist conception by Robert Hurt (NASA: SSC)
Spiral Arm Pitch Angles

• For a log-periodic spiral:
  \[
  \log( R / R_{\text{ref}} ) = -\left( \beta - \beta_{\text{ref}} \right) \tan \psi
  \]

• Outer spiral arms: \(~13^\circ\) pitch angles

• Inner arms may have smaller pitch angels (need more observations)
\[ \Theta_o \approx 220 \text{ km/s} \]
\[ V_{\text{sun}} \approx 20 \text{ km/s} \]

Convert observations from Heliocentric to Galactocentric coordinates.
The Milky Way’s Rotation Curve

$\Theta_0 = 245 \text{ km/s}$

$\Theta_0 = 220 \text{ km/s}$

Blue points moved up 25 km/s
Modeling Parallax & Proper Motion Data

Data: have complete 3-D position and velocity information for each source:

Independent variables: $\alpha, \delta$

Data to fit: $\pi, \mu_\alpha, \mu_\delta, V$

Data uncertainties include:
- measurement errors
- source "noise" of 7 km/s per component (Virial motions in MSFR)

Model: Galaxy with axially symmetric rotation:

$R_0$ Distance of Sun from G. C.
$\Theta_0$ Rotation speed of Galaxy at $R_0$
$\partial \Theta / \partial R$ Derivative of $\Theta$ with $R$: $\Theta(R) \equiv \Theta_0 + \partial \Theta / \partial R \ (R - R_0)$

$U_{\text{sun}}$ Solar motion toward G. C.
" " in direction of Galactic rotation
" " toward N. G. P.

$V_{\text{sun}}$

$W_{\text{sun}}$

$<U_{\text{src}}>$ Average source peculiar motion toward G. C.
" " " " " " " " " " in direction of Galactic rotation

$<V_{\text{src}}>$
“Outlier-tolerant” Bayesian fitting

Prob(Di|M, si) \propto \exp(- R_i^2 / 2)

R_i = (D_i - M_i) / \sigma_i

Prob(Di|M, si) \propto (1 - \exp(- R_i^2 / 2)) / R_i^2

Sivia “A Bayesian Tutorial”
## Model Fitting Results for 93 Sources

<table>
<thead>
<tr>
<th>Method / Rotation Curve used</th>
<th>$R_0$ (kpc)</th>
<th>$\Theta_0$ (km/s)</th>
<th>$d\Theta/dR$ (km/s/kpc)</th>
<th>$&lt;V_{src}&gt;$ (km/s)</th>
<th>$&lt;U_{src}&gt;$ (km/s)</th>
<th>$\Theta_0/R_0$ (km/s/kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Outlier-tolerant&quot; Bayesian fitting Flat Rotation Curve</td>
<td>8.39 ± 0.18</td>
<td>245 ± 7</td>
<td>[0.0]</td>
<td>-8 ± 2</td>
<td>5 ± 3</td>
<td>(28.2)</td>
</tr>
<tr>
<td>Sloped &quot; &quot;</td>
<td>8.38 ± 0.18</td>
<td>243 ± 7</td>
<td>-0.4 ± 0.7</td>
<td>-8 ± 2</td>
<td>6 ± 2</td>
<td>(29.0)</td>
</tr>
<tr>
<td>Least-Squares fitting: removing 13 outliers (&gt;3σ):</td>
<td>8.30 ± 0.09</td>
<td>244 ± 4</td>
<td>-0.3 ± 0.4</td>
<td>-8 ± 2</td>
<td>5 ± 2</td>
<td>(29.4)</td>
</tr>
</tbody>
</table>

Notes:
- Assuming Solar Motion V-component = 12 km/s (Schönenrich et al 2010)
- $<V_{src}>$ = average deviation from circular rotation of maser stars
- $<U_{src}>$ = average motion toward Galactic Center
- $\Theta_0/R_0 = 28.8 \pm 0.2$ km/s/kpc from proper motion of Sgr A* (Reid & Brunthaler 2004)
The Milky Way’s Rotation Curve

- For $R_0 = 8.4$ kpc, $\Theta_0 = 243$ km/s
- Assumes Schoenrich Solar Motion
- Corrected for maser counter-rotation

New and direct result based on 3-D motions “gold standard” distances
Conclusions

• VLBA, VERA & EVN parallaxes tracing spiral structure of Milky Way

• Milky Way has 4 major gas arms (and minor ones near the bar)

• Outer arm spiral pitch angles ~13°

• Star forming regions “counter-rotate” by ~8 km/s (for $V_{\text{sun}}=12$ km/s)

• Parallax/proper motions: $R_0 \sim 8.38 \pm 0.18$ kpc; $\Theta_0 \sim 243 \pm 7$ km/s/kpc
Conclusions

• VLBA, VERA & EVN parallaxes to massive young stars (via masers) tracing spiral structure of Milky Way

• Milky Way has 4 major gas arms (and minor ones near the bar)

• Outer arm spiral pitch angles ~13°

• Star forming regions “counter-rotate” by ~8 km/s (for $V_{sun} = 12$ km/s)

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G.C. stellar orbits + Sgr A* p.m.: $R_0 \sim 8.2 \pm 0.3$ kpc; $\Theta_0 \sim 236 \pm 10$ km/s/kpc
Is $\Theta_0$ really >220km/s?

- Parallax/Proper Motions of Star Forming Regions
  
  $R_0 = 8.4 \pm 0.2$ kpc & $\Theta_0 = 243 \pm 7$ km/s
  
  $\Theta_0 / R_0 = 29.0 \pm 0.9$ km/s/kpc

  (assuming Schoenrich, Binney & Dehnen 2010 Solar Motion)

- Sgr A*’s proper motion (caused by Sun’s Galactic orbit)
  
  $\Theta_0 / R_0 = 28.62 \pm 0.15$ km/s/kpc

  (Reid & Brunthaler 2004)

IR stellar orbits

$R_0 = 8.3 \pm 0.3$ kpc

(Ghez et al 2008; Gillessen et al 2009)

Hence, $\Theta_0 = 238 \pm 9$ km/s

- Combined result:

  $\Theta_0 = 241 \pm 6$ km/s
Carbon Monoxide (CO) Longitude-Velocity Plot

Dame, Hartmann & Thaddeus (2001)
Counter-Rotation of Star Forming Regions

Compute Galacto-centric V
Transform to frame rotating at $\Theta_0 = 250$ km/s (yellow)
See peculiar (non-circular) motions …clear counter-rotation

Transform to frame rotating at $\Theta_0 = 235$ km/s (red)
Still counter-rotating
### Sensitivity to Rotation Curve

<table>
<thead>
<tr>
<th>Method / Rotation Curve used</th>
<th>$R_0$ (kpc)</th>
<th>$\Theta_0$ (km/s)</th>
<th>$\frac{d\Theta}{dR}$ (km/s/kpc)</th>
<th>C.R. (km/s)</th>
<th>G.C. (km/s)</th>
<th>$\frac{\Theta_0}{R_0}$ (km/s/kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Rotation Curve</td>
<td>8.51 ± 0.25</td>
<td>244 ± 9</td>
<td>5 ± 2</td>
<td>5 ± 3</td>
<td>(28.6)</td>
<td></td>
</tr>
<tr>
<td>Sloped ““</td>
<td>8.53 ± 0.27</td>
<td>246 ± 9</td>
<td>1.1 ± 0.9</td>
<td>6 ± 2</td>
<td>5 ± 3</td>
<td>(28.9)</td>
</tr>
<tr>
<td>Brand-Blitz formulation</td>
<td>8.64 ± 0.28</td>
<td>250 ± 9</td>
<td>.06 ± .03</td>
<td>[0]</td>
<td>6 ± 2</td>
<td>5 ± 3 (29.0)</td>
</tr>
<tr>
<td>Polynomial formulation</td>
<td>8.77 ± 0.32</td>
<td>253 ± 10</td>
<td>-1.0 ± 1 -1.5 ± .5</td>
<td>5 ± 2</td>
<td>5 ± 3</td>
<td>(28.8)</td>
</tr>
<tr>
<td>“Universal” formulation</td>
<td>8.80 ± 0.30</td>
<td>250 ± 11</td>
<td>1.1 ± .2 1.6 ± .7</td>
<td>5 ± 2</td>
<td>5 ± 3</td>
<td>(28.4)</td>
</tr>
</tbody>
</table>

#### “Error-tolerant” Bayesian fitting:  
$\text{Prob}(D_i|M) \propto \left( 1 - \exp(- R_i^2 /2) \right) / R_i^2$  
where $R_i = (D_i - M_i) / \sigma_i$

### R.C. params
- $a_1$
- $a_2$

#### Brand-Blitz
\[ \Theta = \Theta_0 \rho^{a_1} + a_2 \]

#### Polynomial
\[ \Theta = \Theta_0 + a_1 (\rho - 1) + a_2 (\rho - 1)^2 \]

#### Universal
\[ \Theta = f( \Theta_0, R_{opt} = a_1, R_0, L = a_2 L_*) \]
Sgr A*’s Proper Motion

\[ \mu = \frac{\Theta_0 + V}{R_0} \]

220 km/s
8.4 kpc
Proper Motion of Sgr A*

- Parallel to Galactic Plane:
  \[ \Theta_o/R_o = 28.62 \pm 0.15 \text{ km/s/kpc} \]
  (after removing \( V=12 \text{ km/s} \))

Remove \( \Theta_o/R_o = 29.4 \pm 0.9 \text{ km/s/kpc} \)

Sgr A*’s motion \( \parallel \) to Gal. Plane
  \[ -7.2 \pm 8.5 \text{ km/s} \ (R_o/8 \text{ kpc}) \]

- Perpendicular to Gal. Plane:
  \[ -7.6 \pm 0.7 \text{ km/s} \]

Remove 7.2 km/s motion of Sun

Sgr A*’s motion \( \perp \) to Gal. Plane
  \[ -0.4 \pm 0.9 \text{ km/s} \]!
Effects of Increasing $\Theta_0$

- Reduces kinematic distances: $D_k$ by 15%, hence...
  - Molecular cloud sizes ($R \propto \varphi D$) by 15%
  - Young star luminosities: $L \propto R^2$ by 30% (increasing YSO ages)
  - Cloud masses (from column density & size): $M \propto R^2$ by 30%

- Milky Way’s dark matter halo mass:
  $$M \propto (V_{\text{max}})^2 R_{\text{Vir}}$$
  $$V_{\text{max}} \propto \Theta_0 \quad \& \quad R_{\text{Vir}} \propto \Theta_0$$
  $$M \propto \Theta_0^3 \quad \text{or up by 50%}$$

- Increasing $\Theta_0$, increases expected dark matter annihilation signals

- Largest uncertainty for modeling Hulse-Taylor binary pulsar timing is accounting for the acceleration of the Sun in its Galactic Orbit: $\Theta^2/R_0$
Effects of Increasing $\Theta_0$

- 1) Increases mass and overall size of Galaxy
- 2) Decreases velocity of LMC with respect to M.W.

Both help bind LMC to M.W. (Shattow & Loeb 2009)

- Increases likelihood of an Andromeda-Milky Way collision