The Synergy between VLBI and Gaia astrometry
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Bessel S269:
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BAADE survey:
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Ylva Pihlström (UNM)
Mike Rich (UCLA)
& BAADE team
Synergy VLBI & Gaia

- Advocating the value of VLBI astrometry
  - of Galactic maser sources
- Now Gaia has delivered

- Complementary in many aspects
  - Distances to individual objects
    - Pinpointing central object in molecular environment
  - Studying stellar populations
  - Detailed structure of the Galaxy
    - Spiral arms, embedded HMSF regions
    - Bulge & Bar, even through optical extinction
  - Kinematic parameters of the Galaxy
    - Size
    - Rotation curve

\[ \pi = 3.67 \pm 0.27 \text{mas} \]

For Gaia - ICRF comparison: Jacobs talk, Charlot poster
Overwhelming Gaia output...

- **Focus on Galaxy construction**
  - Bears on structure formation in the Universe
  - Can we deduce recent and ongoing mergers?
  - What is the (spiral) type of our Galaxy
  - Its star formation rate and its history

- **Understand stellar populations**
  - Kinematics, distribution, age, metallicity

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**Phase space cut, Katz et al. 2018**

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**The Gaia look**
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The Gaia look
Gaia vs VLBI parallaxes

- Gaia DR2: 5 parameter solution
- Accuracies can be comparable
- Water masers still win

From many sources, including:
- Loinard et al,
- Vlemmings & van Langevelde 2007, Kamezaki et al. 2016,
- Nakagawa et al. 2014,
- Kamezaki et al. 2012,
- Nyu et al 2011,
- Min et al. 2014,
- Nakagawa et al. 2008,
- Vlemmings et al 2004,
- Zhang et al. 2017,
- Nagakawa et al. 2016
- Jennings et al. 2018
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Understanding the differences

- Gaia zero point offset
  - Quite large when determined from this sample
- Giants have large Gaia residuals
- Structure and (colour) variability of photosphere
  - Convection related variability (Chiavassa et al. 2018)
- Some stars too bright…

Statistics seem OK when:

- Shifting by parallax offset
- And adding the excess noise
- VLBI parallaxes still valuable
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BeSSeL survey

- Progress to improve coverage
  - > 100 new targets
  - Largely with VLBA 6.7 GHz
- Best way to measure MW parameters
  - Demonstrated to bias-free
- Unique for localising spiral arms

See also talks by Immer, Rygl

Quiroga-Nunez et al., 2017
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Spiral arms by Reid et al. 2014

Quiroga-Nunez et al., 2017

See also talks by Immer, Rygl
BeSSeL source S269

- Recent result with VLBA
  - Previous VERA results controversial
  - Now 12 VLBA epochs and better image fidelity
- Confirming the closer distance
  - Is it in the Outer arm?
  - Is the Outer arm closer than previously thought?

water masers in S269 Quiroga Nunez et al 2018

π = 0.241 ± 0.012 mas

S269 wrt J0613+1306
Associated young stars?

- Next to S269 is NGC 2194
  - Similar distance
  - PM not inconsistent
  - Maser motions measured
  - Separated from core of cluster
- But in principle associated stars are expected
  - Can be used to refine distances
  - Maybe even ages
BAaDE project

- Bulge Asymmetries and Dynamic Evolution
  - Going for Mira stars with SiO masers
  - IR selection based on MSX
- Concentrated on $|b| < 5^\circ$
  - No optical data, but kinematics of bar
- 30,000 targets
  - VLA 19,000 observations complete
    - Very fast detection experiment
    - No time for phase calibration
  - ALMA ongoing
So, you want to do SiO astrometry?

- **Current practice of cross-calibration**
  - Coherence time short
  - Calibrators weak and few
  - Region of interest is central Galaxy, low dec
  - A-priori positions poor
  - SiO masers close to stars and variable

- Do 100–200 stars in the bar?

- **Addressing these limitations:**
  - Test observations with various parameters
  - Calibrator surveys
  - Explore non-imaging astrometry
  - Consider K/Q cross calibration?

SiO ring OH44 at 1.2kpc
Amiri et al., 2012

Inferring (point) source properties and phase calibration simultaneously
Preliminary simulations with Natarajan & Deane
View on inner Galaxy

- BAaDE samples disk and bar
  - Kinematics & population analysis
- Cannot be reached by Gaia
  - But overlap Gaia - BAaDE sample can constrain

$l = 0.0$
$l = 4.5$
$l = 9.0$
$l = 13.5$
$l = 18.0$
$l = 22.5$
$l = 27.0$
$l = 31.5$
$l = 36.0$


SiO maser candidates identified in Gaia DR2 with accurate distances Quiroga-Nunez in prep
BAaDE targets without Gaia counterparts

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\[ \pm 0.5 \text{ kpc} \]

A_p \geq -1.5
A_p < -1.5

Perspecical calibration

SiO maser candidates identified in Gaia DR2 with accurate distances Quiroga-Nunez in prep

Work in progress: characterising population

- From 28,000 targets
  - 20,000 have 2Mass, Gaia counterpart
    - But must include some false positives
  - 2,554 have $\sigma_\pi/\pi < 0.2$
  - Of which 172 have SiO masers detected

- So far consistent with LPV AGB stars
  - As expected
  - Towards progenitor mass and age

BAaDE targets with Gaia distances
Future

- New telescopes can improve VLBI:
  - High mass star forming regions
    - Southern hemisphere campaigns (AuScope)
    - African VLBI Network developments
      - Refurbished communication dishes
    - SKA1-Mid will have VLBI capabilities
      - And receiver (band 5) for methanol (and water)
      - Major improvements in SNR and calibrator coverage
  - Evolved stars
    - VERA important for water masers
    - Simultaneous water and SiO masers on Korean telescopes
    - SiO masers on VLBA to be tested
      - progress with mm VLBI
      - may be targets for ngVLA long baselines

BeSSeL simulations featured on the SKA calendar on display in Dr. Koothrappali’s office (Quiroga-Nunez et al., 2017)
Synergy VLBI — Gaia

- previous VLBI astrometry OK
  - Gaia errors not trivial for AGB stars

- VLBI measuring spiral structure
  - And overall MW parameters

- May reach inner Galaxy kinematics
  - Gaia valuable for characterising population

- AVN & SKA will contribute

Credit to Luis-Henry Quiroga-Nuñez