Astrometric Observations of Neutron Stars

Shami Chatterjee

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Overview

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  - Case Study: High velocity pulsars.
  - Case Study: Proper motion of a transient source.
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  - Case Study: High velocity pulsars.
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- Attaining high precision.

- Results and future directions.
Neutron Star Astrometry

- Basic observable: \textbf{Position} $\vec{\theta}$.  
  $\rightarrow$ Celestial coordinate grid defined by the ICRF.
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- Positions over time: Proper motion $\vec{\mu}$.
  → Longer time baseline helps measurement.
  → Reference frame and calibrator stability?
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- Positions from different points in Earth’s orbit: Parallax $\pi$.
  → Frequent sampling over the orbit helps measurement.
Neutron Star Astrometry

→ Optical / IR.
  (e.g., HST $\pi$ to RX J0720.4–3125, Kaplan et al.)

→ X-ray.
  (e.g., CXO $\mu$ of NS in Puppis A, Winkler & Petre.)

→ Radio pulse timing of recycled pulsars.
  (e.g., J0437–4715; van Stratten, Bailes, et al.)

→ Radio interferometry.
The majority of NS parallaxes are from VLBI.
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Motion of B0950+08

$\mu_\alpha = -2.06 \pm 0.07 \text{ mas/yr}$

$\mu_\delta = 29.37 \pm 0.05 \text{ mas/yr}$

$\pi = 3.81 \pm 0.07 \text{ mas}$

(Brisken et al. 2000 ++)

Neutron Star Astrometry
Neutron Star Astrometry

(Brisken et al. 2000 ++)

\[ \{\mu, \pi\} \Rightarrow \text{Model-independent distances and velocities.} \]
Why do it?
(What’s in it for me?)
Why Measure Velocities and Distances?

- **Astrophysics**: NS atmospheres, cooling curves and nuclear Equations of State from spectra and absolute distances.
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(e.g., Lattimer & Prakash 2006, Yakolev et al. 2007)
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- **Astrophysics**: Constraints on supernova core collapse.

(e.g., Spruit & Phinney 1998, Deshpande et al. 1999, Lai et al. 2001, etc.)
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• **Origins**: SNR associations and NS birth sites; true ages.

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(e.g., Arzoumanian et al. 2001, Hobbs et al. 2005, Faucher-Giguère & Kaspi 2006, etc.)
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- **Environment**: Calibrate models of Galactic $n_e$ density.
- **Environment**: Model the local ISM with ISS, bow shocks.

(e.g., Taylor & Cordes 1993, Cordes & Lazio 2001, etc.)
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- **Verify solar system–extragalactic reference frame ties**.

(e.g., Bartel et al. 1996; also Fomalont & Reid 2007)
Case study: PSR B1508+55

How large are the kicks that NS receive at birth?
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B1508+55 is a very “ordinary” pulsar:

- Rotation period is 0.74 seconds.
- Inferred magnetic field is $2 \times 10^{12}$ Gauss.
- Characteristic age is 2.3 million years.
- Located well outside Galactic plane ($b = 52.3^\circ$).
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Observe 8 times over 2 years with the VLBA...
Astrometric Results for B1508+55

\[ \mu_a = -73.61 \pm 0.04 \text{ mas yr}^{-1} \]
\[ \mu_d = -62.62 \pm 0.09 \text{ mas yr}^{-1} \]
\[ \pi = 0.42 \pm 0.04 \text{ mas} \]

(with Vlemmings, Brisken, Lazio, Cordes, Goss, Thorsett, Fomalont, Lyne, Kramer)
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The highest measured model-independent velocity yet!

(Chatterjee et al. 2005)
The Birth Site of B1508+55

- Current Galactic latitude = 52.3°.
- Trace back orbit in Galaxy: born in Galactic plane.
- Birth in or near Cygnus OB associations.
B1508+55: Getting its Kicks

- **B1508+55**: implied birth velocity $\approx 1100 \text{ km s}^{-1}$.
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- Core collapse: first 3D hydrodynamic simulations (Fryer 2004) do not produce such large kicks.

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$\Rightarrow$ High velocities impose severe constraints on core collapse and kick velocity scenarios.
Case study: A Magnetar Proper Motion

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- Experiment: Turn up the magnetic field.
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• Experiment: Turn up the magnetic field. ⇒ Are magnetar velocities \(\gg\) ordinary psr velocities?

• Need X-ray or adaptive optics IR obs over many years.

→ Interesting preliminary results. (e.g., two-epoch \textit{Chandra} obs; Kaplan et al. 2009), But we need longer time baselines.
- Camilo et al. (2006): Transient pulsed radio emission!
- Rapidly fading...

(from Camilo et al. 2006)
Camilo et al. (2006): Transient pulsed radio emission!

- Rapidly fading...

- But bright enough for VLBA obs at 5, 8.4 GHz over 106 days.
\[ \mu_\alpha = -6.60 \pm 0.06 \ \text{mas yr}^{-1} \]
\[ \mu_\delta = -11.7 \pm 1.0 \ \text{mas yr}^{-1} \]

\[ \Rightarrow \]

For \( D = 3.5 \pm 0.5 \ \text{kpc}, \)
\[ V_\perp \sim 220 \ \text{km s}^{-1} \]
\[ [180 - 270 \ \text{km s}^{-1}] \]

(Helfand, Chatterjee, et al. 2007)
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(Helfand, Chatterjee, et al. 2007)

\[ \Rightarrow \text{For this one magnetar } V_\perp \text{, no exotic kicks are required.} \]
How do we do it?
Astrometric observations are phase-referenced: ICRF.
Pulsar Astrometry with the VLBA

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- Boost S/N ratio for pulsars with the pulsar gate.
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A systematic approach to In-beam Calibration

- Image the VLA 1.4 GHz primary beam (25');
  Identify compact sources.

63 target fields = 1060 sources detected (\(~16\) / field).
A systematic approach to In-beam Calibration

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- Verify compactness at higher frequencies with VLA.

269 apparently compact sources imaged (∼4 / field).
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- Image with the VLBA.

55 out 63 targets had 1 or more in-beam calibrator.
A systematic approach to In-beam Calibration

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- Verify compactness at higher frequencies with VLA.
- Image with the VLBA.

- Observe over 2 years:
  → 8 epochs: $\{\pi_{\text{max}}, \pi_{\text{min}}\}$.
  → 4 frequency bands, dual polarization, 256 Mb/s.
  ⇒ High quality astrometry.
A systematic approach to Systematic Errors

- Bootstrap: infer uncertainties from the data itself.
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- 8 epochs $\times 4$ frequencies $= 32$ astrometric positions.
  $\rightarrow$ Choose values *with replacement*.
  $\Rightarrow 32^{32}$ combinations possible (but some are degenerate).
A systematic approach to Systematic Errors

• Bootstrap: infer uncertainties from the data itself.

• $8 \times 4 = 32$ astrometric positions.
  → Choose values with replacement.
  ⇒ $32^{32}$ combinations possible (but some are degenerate).
  → Explore $\sim 10,000$ fits...
A systematic approach to Systematic Errors

Normal case: Bootstrap results for B0818–03
A systematic approach to Systematic Errors

Worst case: Bootstrap results for J1713+0747
Southern hemisphere

- Long Baseline Array
  (Parkes, ATCA, Mopra, Tidbinbilla; +Hobart? +Ceduna?)
⇒ Shorter baselines, poorer UV coverage, tougher calibration.
Southern hemisphere

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  \[\Rightarrow\] Shorter baselines, poorer UV coverage, tougher calibration.

\[\Rightarrow\] Note ASKAP under construction in Western Australia.
Southern hemisphere

- Long Baseline Array
  (Parkes, ATCA, Mopra, Tidbinbilla; +Hobart? +Ceduna?)
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- Fantastic parallax measurements by Deller et al. (2008, 2009).

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PSR J0108−1431

PSR J0630−2834
Where do we stand?
And what next?
Both quantity and quality

- Individual measurements can be extremely valuable.
  - e.g., Astrometry on binary pulsars ⇒ GR.
  - e.g., Case studies outlined in this talk.
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  → e.g., Astrometry on binary pulsars ⇒ GR.  
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- A large ensemble of measurements enables deeper insights.  
  → e.g., Velocities ⇒ supernova core collapse.  
  → e.g., Electron density models.
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Large samples test models, enable refinements (Chatterjee et al. 2009)
High Sensitivity VLBI

- Larger samples require higher sensitivities, better techniques.
  → VLBA bandwidth expansion.
  → High sensitivity arrays.
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High Sensitivity VLBI

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  - VLBA bandwidth expansion.
  - High sensitivity arrays.

... but larger telescopes
  ⇒ smaller FoV;
  ⇒ harder calibration;
  ⇒ trickier phase referencing.
- GPS Ionospheric calibration: capabilities improving.
Technical Progress

- GPS Ionospheric calibration: capabilities improving.
- Focal plane arrays: eliminate need to slew for phase referencing?

Parkes testbed FPA; CSIRO July 2008
Final Thoughts and Future Directions

- Precision astrometry enables unique science.
  - The origins, evolution, astrophysics, environments of NS.
  - e.g., Constraints on supernova core collapse, NS kicks.
Final Thoughts and Future Directions

• Precision astrometry enables unique science.
  → The origins, evolution, astrophysics, environments of NS.

• The importance of a consistent, systematic approach.
  → Control of systematic errors essential.
  → Larger field of view ⇒ more inbeam sources.
  → More sensitivity ⇒ higher $\nu_{\text{obs}}$ as well.
Final Thoughts and Future Directions

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  → The origins, evolution, astrophysics, environments of NS.

• The importance of a consistent, systematic approach.

• Future instruments, technology, techniques:
  → Ionospheric calibration: GPS.
  → Focal plane arrays: vastly larger FOVs.
  → SKA: mas resolution required for the $\mu$Jy sky

  ⇒ High precision radio astrometry.
A long but incomplete list:

Jim Cordes (Cornell), Bryan Gaensler (Sydney),
Miller Goss, Walter Brisken, Adam Deller (NRAO),
Wouter Vlemmings, Andrew Lyne, Michael Kramer (Jodrell),
Joe Lazio (NRL), Zaven Arzoumanian (NASA GSFC),
Stephen Thorsett (UCSC), Don Backer (UC Berkeley),
Ed Fomalont, John Benson, Mark McKinnon (NRAO),
David Kaplan (UCSB), David Helfand, Fernando Camilo (Columbia),
and many others ...

Pulsar Astrometry: http://www.astro.cornell.edu/~shami/psrvlb/