Neutron Stars, Radio Transients, and Precision Astrometry

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• Science makes progress through the interplay between theory and observation.
• Crucial role of precision measurements.
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Crucial role of precision measurements.

In this talk:

- Precision astrometry of neutron stars:
  - Supernova core collapse.
  - Gamma ray emission energetics.

- Radio transients:
  - VAST, an ASKAP Survey Science program.
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...
$\mu_a = -73.61 \pm 0.04 \text{ mas yr}^{-1}$

$\mu_d = -62.62 \pm 0.09 \text{ mas yr}^{-1}$

$\pi = 0.42 \pm 0.04 \text{ mas}$

(with Vlemmings, Brisken, Lazio, Cordes, Goss, Thorsett, Fomalont, Lyne, Kramer)
Astrometric Results for B1508+55

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Distance = \( 2.37^{+0.23}_{-0.20} \) kpc
\[ V_\perp = 1083^{+103}_{-90} \, \text{km s}^{-1} \]

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(Chatterjee et al. 2005)

The highest measured model-independent velocity yet!
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.

Orbit of B1508+55 overlaid on Axel Mellinger’s image of the Galaxy.
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B1508+55: Getting its Kicks

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- High kick velocity poses a challenge for core collapse simulations and proposed kick mechanisms.

$\rightarrow$ We can also do this for other compact radio sources, of course...
• 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.
\(\mu_\alpha = -6.60 \pm 0.06 \text{ mas yr}^{-1}\)

\(\mu_\delta = -11.7 \pm 1.0 \text{ mas yr}^{-1}\)
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\[ \Rightarrow \]

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)

$\Rightarrow$ For this one magnetar $V_\perp$, no exotic kicks are required.
The *Fermi* gamma-ray space telescope

- LAT: Imaging high-energy gamma-ray telescope.
- 20 MeV—300 GeV; FoV covers 20% of the sky.
- Continuous scanning: whole sky imaged every 3 hours.
Note: Crab, Vela, Geminga, J1836+5925, and “Unidentified”...
A neutron star discovery machine!

New Millisecond Radio Pulsars Found in Fermi LAT Unidentified Sources

Led by Fernando Camilo (Columbia Univ.) using Australia’s CSIRO Parkes Observatory
Led by Mallory Roberts (Eureka Scientific/GMU/NRL) using the NRAO’s Green Bank Telescope
Led by Scott Ransom (NRAO) using the Green Bank Telescope
Led by Ismael Cognard (CNRS) using France’s Nançay Radio Telescope
Led by Mike Keith (ATNF) using Parkes Observatory

(Scott Ransom, Paul Ray, AAS meeting 215, DC 2010)
First *Fermi* PSR catalog: 46 gamma-ray pulsars!

→ 16 new pulsars from γ-ray blind searches.

→ Many more from radio follow-up of unidentified point sources.

→ More discoveries on a regular basis.

→ Young + recycled.
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- High $B_{LC}$ $\Leftrightarrow$ $\gamma$-ray emission?
- Interesting physics to be sorted out.
Gamma ray luminosity vs Spindown $\dot{E}$
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Suggestive? But distance uncertainty limits usefulness...
Case study: PSR J1614–2230

- Mass from Shapiro delay = $1.97(4) \, M_\odot$ (Demorest et al. 2010).

⇒ Rules out most exotic quark matter equations of state.
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- At D=1.2 kpc, $L_\gamma$ is also $\gtrsim 100\%$ of $\dot{E}$.

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  ⇒ A precise distance may constrain the NS moment of inertia.
Astrometry is a force multiplier: precise astrometry improves the science return from new discoveries.
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- **Astrophysics**: NS kicks constrain models of supernova core collapse – hydrodynamic, magnetic field-driven, or hybrids.

- **Astrophysics**: Compare apparent L$_\gamma$ with absolute $\dot{E} = I \omega \dot{\omega}$.

  → Emission geometry, luminosity evolution.
Astrometry is a force multiplier: precise astrometry improves the science return from new discoveries.

- **Origins**: Use $\mu$ and $\tau$ to trace path back to birth sites and associations with massive star clusters, SNRs.
- **Relativistic winds**: Calibrate energetics of PWNe, probe interaction with ISM and bulk flows.
Astrometry is a force multiplier: precise astrometry improves the science return from new discoveries.

- **Gravitational physics**: Astrometric parameters for stable recycled pulsars independent of pulse timing.
  → Shklovskii effect corrections, break timing degeneracies.

- **Galactic electron density modeling**: improve DM-based distance estimates for entire population.
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- **Astrophysics**: SN core collapse, $L_\gamma$ vs. $\dot{E}$.
- **Origins**: Birth sites, associations.
- **Relativistic winds** and the ISM.
- **Gravitational physics**.
- **Galactic modeling**: $N_e$ distribution.
Two parallel efforts in progress:

- Targeted astrometry on a subset of *Fermi*-detected radio pulsars: 18 targets, 12 being observed (epochs 1–3).
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**VLBA astrometry collaboration:**
Goal: A distance measuring service

Is YOUR Neutron Star:

★ A radio emitter?
★ Brighter than ~1 mJy?
★ Closer than ~8 kpc?
★ North of −25 in Dec?

Measure a parallax* with the VLBA!

*Certain conditions, exclusions, and limitations apply. Please talk to the presenter or consult your friendly local expert about why the VLBA may be right for YOU!
The dynamic radio sky is a discovery frontier. 

*Why?* Trade-off between sky coverage and sensitivity. 
(There are no all-sky monitors at $\sim$GHz frequencies.)
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VAST → “Slow” transients, no dispersion searching.

Ultimately, we want to go from discovery → science.

- Explosive events.
- Accretion-powered.
- Magnetic field driven.
- Propagation effects.
GCRT 1745–3009: Periodic 1 Jy bursts at 330 MHz. 77 min intervals, 10 min bursts... coherent, unexplained.

(Hyman et al. 2005, Nature, 434, 50)
The dynamic radio sky is a discovery frontier.

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don’t know
We don’t know.

— US Sec Def. Donald Rumsfeld
DoD briefing, 12 Feb 2002
Log N—log S distribution of transient and variable sources from different surveys: different $\nu_{\text{obs}}$, cadences, sky coverage, etc.

(Plot from Bell et al. 2011)
ASKAP: The Australian SKA Pathfinder

- Square Kilometer Array: the next generation radio telescope.
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- Under construction; operations commence in 2013.
- 36 dishes, 12-m diameter, 2 km core, up to 6 km baselines.
- Operating at 0.9–1.8 GHz, with $\sim 20''$ beam.

(Oct 2010, with thanks to Ant Schinckel, CSIRO)
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Wide field of view ($\gtrsim 30$ sq deg):
⇒ ASKAP is well-suited for surveys for radio transients.
VAST: An ASKAP Survey for Variables and Slow Transients

- **VAST** is one of 10 approved Survey Science Proposals. Currently starting Year 2 of Design Study.
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  - **76 members**, 36 institutions, 4 continents.
  - PIs Tara Murphy & Shami Chatterjee.
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- Survey components: **Deep, Wide, Galactic Plane**.

- Wide range of science goals, but the same technical challenges:
  - Detection of transients and variable sources.
  - Identification and classification.
  - Triggered follow-up observations.
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  - **Detection** of transients and variable sources.
  - **Identification** and **classification**.
  - Triggered **follow-up** observations.

- **Open collaboration**: We welcome interested and active new members!
A whole generation of students, postdocs, and young radio astronomers owes you a debt of thanks!

Your unflagging enthusiasm has helped drag many a paper across the finish line.

We will look forward to many more marked up paper drafts.

Radio astronomy and transients: we live in interesting times.
Extras
Goal: A distance measuring service

Is **YOUR** Neutron Star:

⭐ A radio emitter?
⭐ Brighter than ~1 mJy?
⭐ Closer than ~8 kpc?
⭐ North of ~25 in Dec?

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- Survey entire sky at regular intervals.
  → Go shallow but wide in search of ‘rare and bright’ sources.
  ⇒ Better sky coverage, poor coverage of different cadences.
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• Also possible:
  • Regular monitoring of specific sources;
  • Triggered observations;
  • Archival searches for longer timescales;
  • ... etc.
VAST Strawman surveys

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• VAST-Wide: 10,000 sq deg observed daily.
  → 40 sec per field; 0.5 mJy/beam; 4380 hrs.
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- VAST-Deep: 30 sq deg observed daily.
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- **VAST-Deep**: 30 sq deg observed daily.
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- **VAST-GP**: 750 sq deg observed 64 times.
  $\rightarrow$ 16 min per field; 0.1 mJy/beam; 600 hrs.
ASKAP is optimized for survey speed: VAST will far exceed existing surveys on that metric.

(Analysis of 30-yr Molonglo archive, Bannister et al. 2011)
ASKAP is optimized for survey speed: VAST will *far exceed* existing surveys on that metric.

Major challenges ahead: what do we do with the data?
- Massive data volume: real-time detection pipeline.
- Reliable automated source finding.
- Multi-wavelength follow-up, source ID, classification.
- Database handling, algorithm development, etc.
Guitar Nebula: $V_\perp = 1640 \text{ km/s}$ at 1.9 kpc

Cordes, Romani, & Lundgren 1993; Chatterjee & Cordes 2002
1994 December: Narrow-band Hα; $T_{\text{int}} = 7200$ s; Drizzled.

Chatterjee & Cordes 2002, 2004
2001 December: Narrow-band H\textsubscript{\alpha}; T\textsubscript{int} = 17600 s; Drizzled.

Chatterjee & Cordes 2002, 2004
• Changing shape, stand-off distance trace changes in ISM.