U.S. NAVAL RESEARCH LABORATORY

In Search of Galactic Center Millisecond Pulsars from Steep-Spectrum, Compact Radio Sources

N. E. Kassim,[1] **S. D. Hyman,[2] D. A. Frail,[3]** J. S. Deneva,[4] M. A. McLaughlin,[5] J. E. Kooi,[1] P. S. Ray,[6] E. J. Polisensky[1]

[1]Naval Research Laboratory, Remote Sensing Division, Washington, DC 20375

[2] Sweet Briar College, Sweet Briar, VA 24595

[3] National Radio Astronomy Observatory, Socorro, NM 87801

[4] George Mason University, Fairfax VA 22030, resident at NRL

[5] West Virginia University, Morgantown, WV 26506

[6] U.S. Naval Research Laboratory, Space Sciences Division, Washington, DC 20375

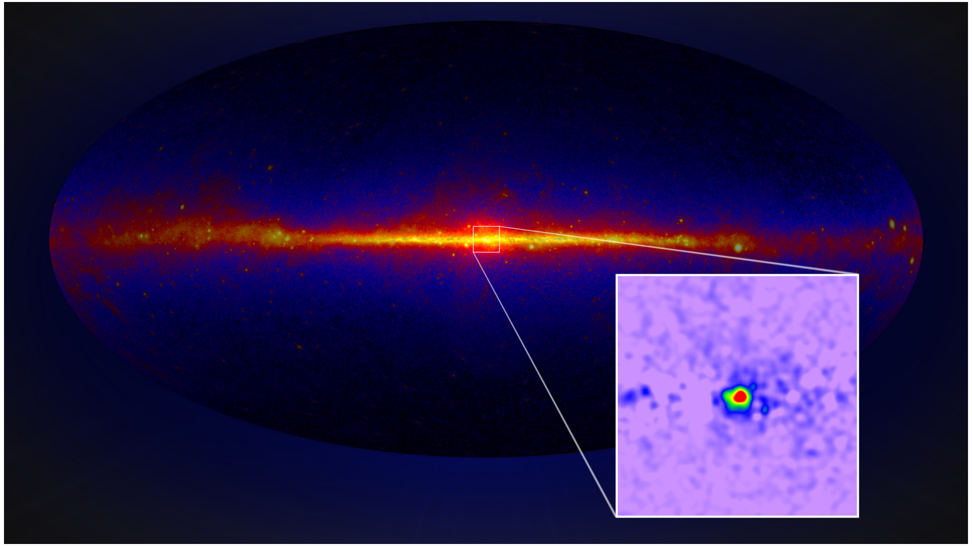
Old Mystery
Where are the GC PSRs?

- Given enhanced gas & stellar densities, long been predicted that the GC harbors large (> 1000) population of NSs (Paczynski & Trimble 1979; Cordes & Lazio 1997; Pfahl & Loeb 2004).
- Some success in finding X-ray binaries (Zhao et al. 1992; Bower et al. 2005, Hauley et al. 2018) and probable pulsar wind nebulae (Park et al. 2005).
- **Only 5 normal pulsars near the GC have been found** - within 15' of Sgr A* (Johnston et al. 2006, Deneva et al. 2009, distances 5.6-8.2 kpc from DMs)
- Serendipitous X-ray discovery of a magnetar (Mori et al. 2013) subsequently detected as radio PSR at multiple frequencies.
- To date **NO MSPs have been detected** in the GC region.
- Low pulsar yield in the GC region has been attributed to **hyperstrong scattering occurring within 100 pc of Sgr A*** (Lazio & Cordes 1998)

Renewed Interest
Fermi ɣ-ray Emission Excess (GRE)

- Fermi shows GRE within radius of ~15° around the GC (Vitale & Morselli 2009; Hooper & Goodenough 2011)
- Earliest interpretations favored DM particle annihilation
- Recent analyses of spatial and spectral properties, using data from the entire Fermi mission, argue it is caused by **population of thousands of MSPs** (Ajello et al. 2016; Bartels et al. 2016; Calore et al. 2016; Lee et al. 2016; Gonthier et al. 2018)

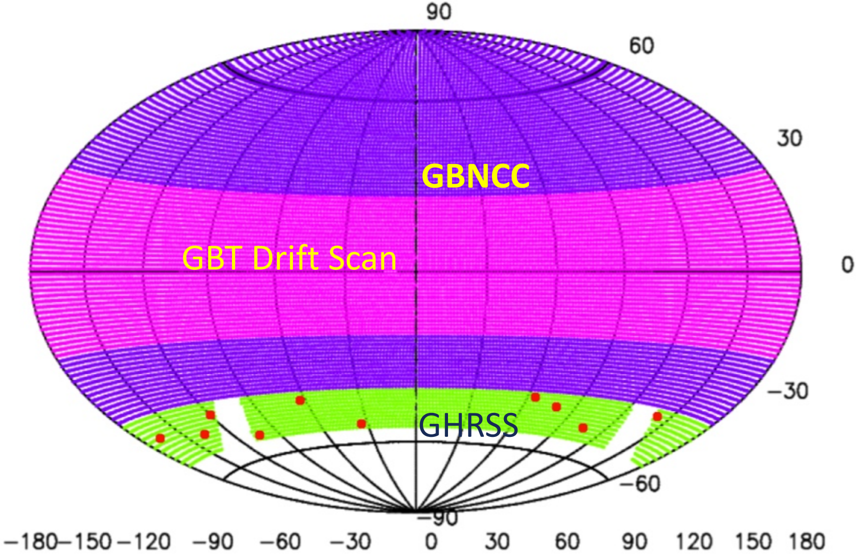
Fermi GC Gamma-ray excess (bulge)

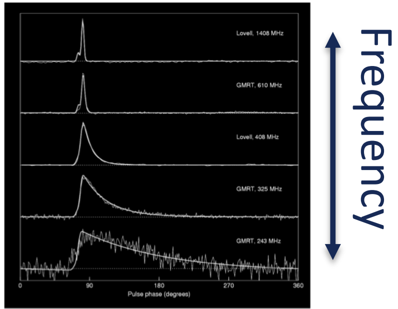


How Can We Find GC MSPs?

- Blind Surveys
  - Systematic search of the sky for periodicity

    e.g. GBT-based North Celestial Cap Survey
  - ***Extremely difficult at the GC!***
- Scattering kills you
  - $\tau_{scat} \propto \nu^{-4}$: therefore need to go to high frequencies
  - But then blind survey is inefficient due to **small field-of-view & *very steep* spectra**





History as a Guide
Finding MSPs in the Imaging Domain

U.S. NAVAL RESEARCH LABORATORY

First isolated millisecond pulsar

letters to nature

Nature **300**, 615 - 618 (16 December 1982); doi:10.1038/300615a0

A millisecond pulsar

D. C. BACKER[*], SHRINIVAS R. KULKARNI[*], CARL HEILES[*], M. M. DAVIS[†] & W. M. GOSS[‡]

[*]Radio Astronomy Laboratory and Astronomy Department, University of California, Berkeley, California 94720, USA
[†]National Astronomy and Ionosphere Center, Arecibo, Puerto Rico
[‡]Kapteyn Laboratorium, Groningen, The Netherlands

The radio properties of 4C21.53 have been an enigma for many years. First, the object displays interplanetary scintillations (IPS) at 81 MHz, indicating structure smaller than 1 arc s, despite its low galactic latitude (−0.3°)[1]. IPS modulation is rare at low latitudes because of interstellar angular broadening. Second, the source has an extremely steep ($\sim\nu^{-2}$) spectrum at decametric wavelengths[2]. This combination of properties suggested that 4C21.53 was either an undetected pulsar or a member of some new class of objects. This puzzle may be resolved by the discovery and related observations of a fast pulsar, 1937+214, with a period of 1.558 ms in the constellation Vulpecula only a few degrees from the direction to the original pulsar, 1919+21. The existence of such a fast pulsar with no evidence either of a new formation event or of present energy losses raises new questions about the origin and evolution of pulsars.

First globular cluster pulsar

letters to nature

Nature **328**, 399 - 401 (30 July 1987); doi:

The discovery of a millisecond pulsar in the globular cluster M28

A. G. LYNE[*], A. BRINKLOW[*], J. MIDDLEDITCH[†], S. R. KULKARNI[‡], D. C. BACKER[§] & T. R. CLIFTON[§]

[*]University of Manchester, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK
[†]Earth and Space Sciences Division, Los Alamos National Laboratory, New Mexico 87545, USA
[‡]Department of Astronomy, Caltech, Pasadena, California 91125, USA
[§]Astronomy Department, University of California, Berkeley 94720, USA

Here we report the discovery of a pulsar with a 3 millisecond period in the core of the globular cluster M28. The existence of a millisecond pulsar in suc[h] a cluster, where there are frequent interactions between cluster stars, provides strong confirmation of the theory that the high rotation rate derives from accretion in a binary system. The pulsar is now isolated, having no binary companion.

Erickson 1980)

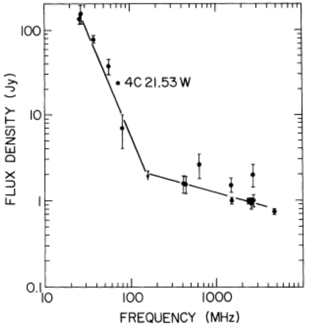


FIG. 2.—The radio spectrum of 4C 21.53W. Data are listed in Table 2. The solid lines correspond to spectral indices of −0.26 (ν > 150 MHz) and −2.44 (ν > 150 MHz).

Hamilton et al (1985)

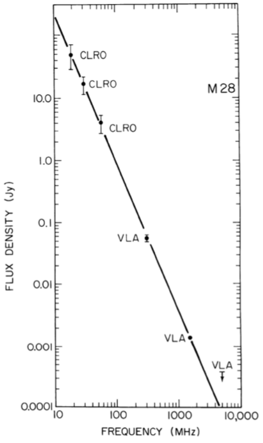


FIG. 1.—The flux density spectrum of M28 derived from VLA and Clark Lake observations. Solid line represents a spectrum of index −2.44.

- Bill Erickson inferred that steep spectrum radio source 4C21.53 was ”fast” PSR

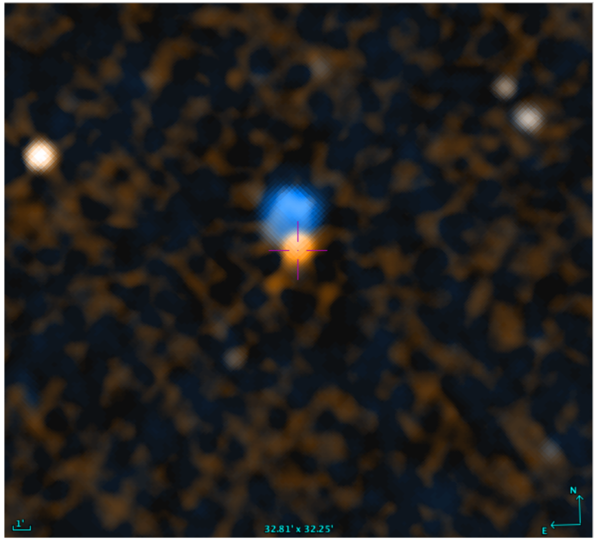
  Its steep spectrum reminded him of the Crab PSR, which was then the fastest known PSR

➢ 4C21.53 was subsequently detected as **first MSP** (PSR B1937+21) by Backer et al.

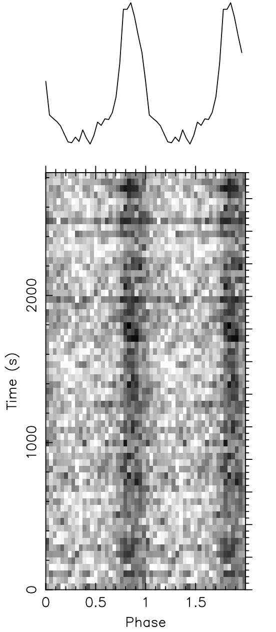
Why has it taken so long to use this approach to find MSPs?

- **Lack of low ν surveys with sufficient angular resolution** crucial for sensitivity & compactness
- Surveys like TGSSr now make that possible
- Can search without regard to period, DM, orbital parameters, or scattering biases
- Promising candidates searched for pulsations in γ-rays and/or radio
- Approach has so far found 5 new MSPs (Frail et al. 2018)

TGSS-NVSS
Spectral Index Image
4C 21.53

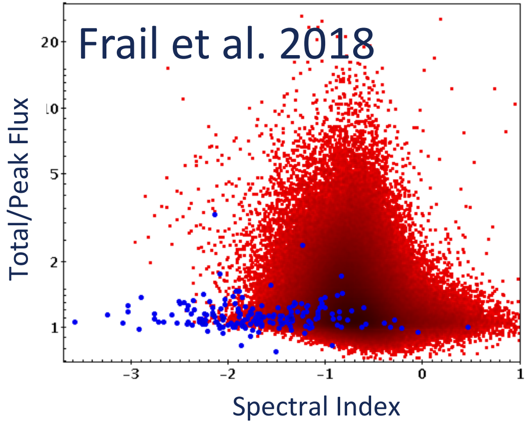


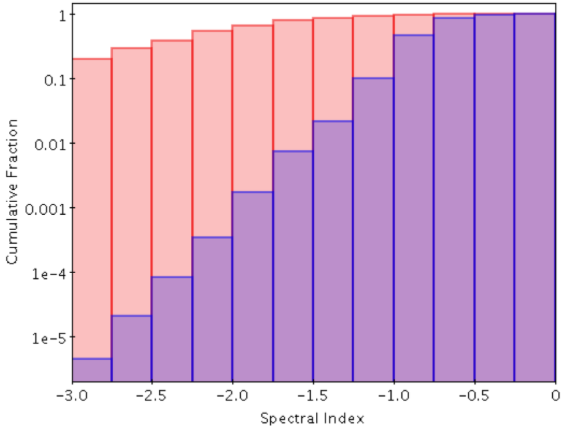
Bhakta et al. 2017 - 2.2 ms PSR, GBT S-band – towards GC but foreground



Quantifying the Approach
MSPs vs. High-z Radio Galaxies

- MSPs are compact, steep-spectrum sources.
  - 75% of PSRs have α ≤ -1.5
  - Only 0.3% of HzRGs have spectra this steep
- From ~450,000 compact TGSSr sources (de Gasperin et al. 2018)
  - 1.5% have α ≤ -1.4
  - 80% of known PSRs are this steep
- For our P-band sample of 375 sources, we do not expect to find any background sources with α < -1.8

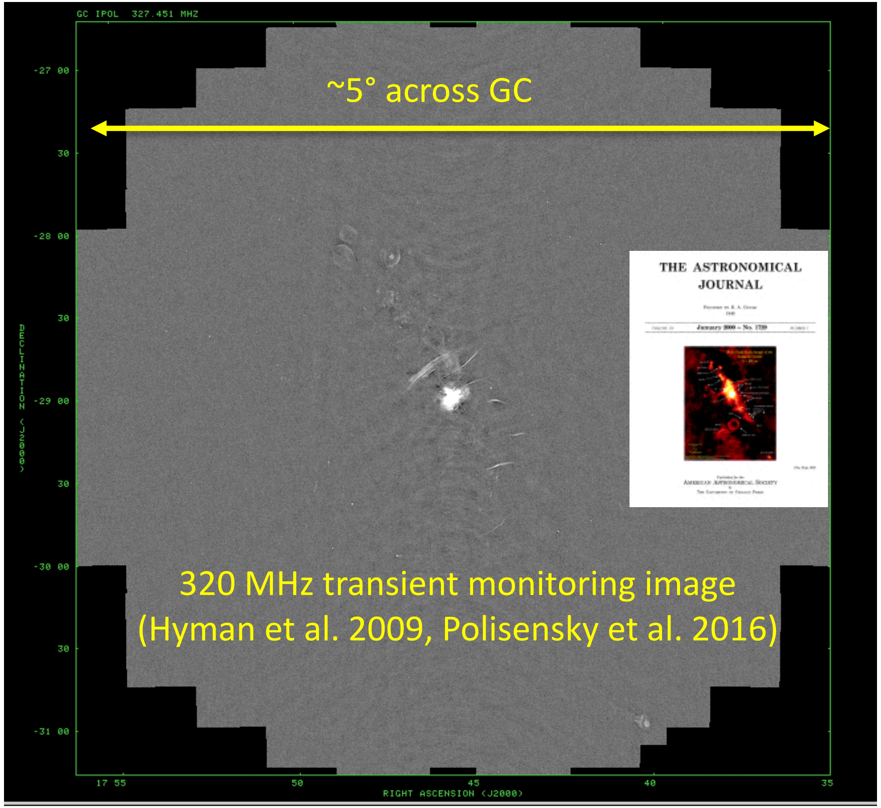




Hyman et al. 2019

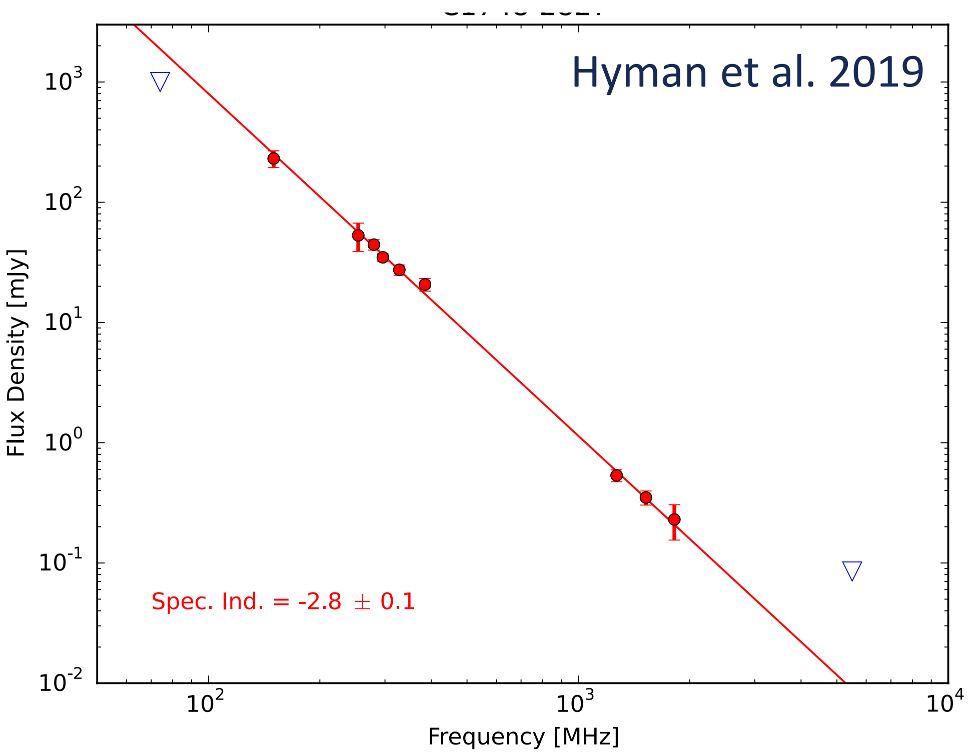
Candidate Selection

- Start with 320 MHz GC image: ~10 deg^2, 0.7 mJy/beam (1 σ)
  - **From 375 sources, 12 selected with $\alpha < -1.4$, $S_{int}/S_{peak} < 1.5$**
- Next step: high ν VLA follow-up imaging
  - **7 candidates** passed α & compactness criteria
- Corresponding minimum L-band luminosities (5 σ)
  - ≥ 32 mJy kpc^2 ($\alpha = -1.4$) @ 1400 MHz
  - ≥ 4 mJy kpc^2 ($\alpha = -2.8$) @ 1400 MHz



Current Results
NADA!

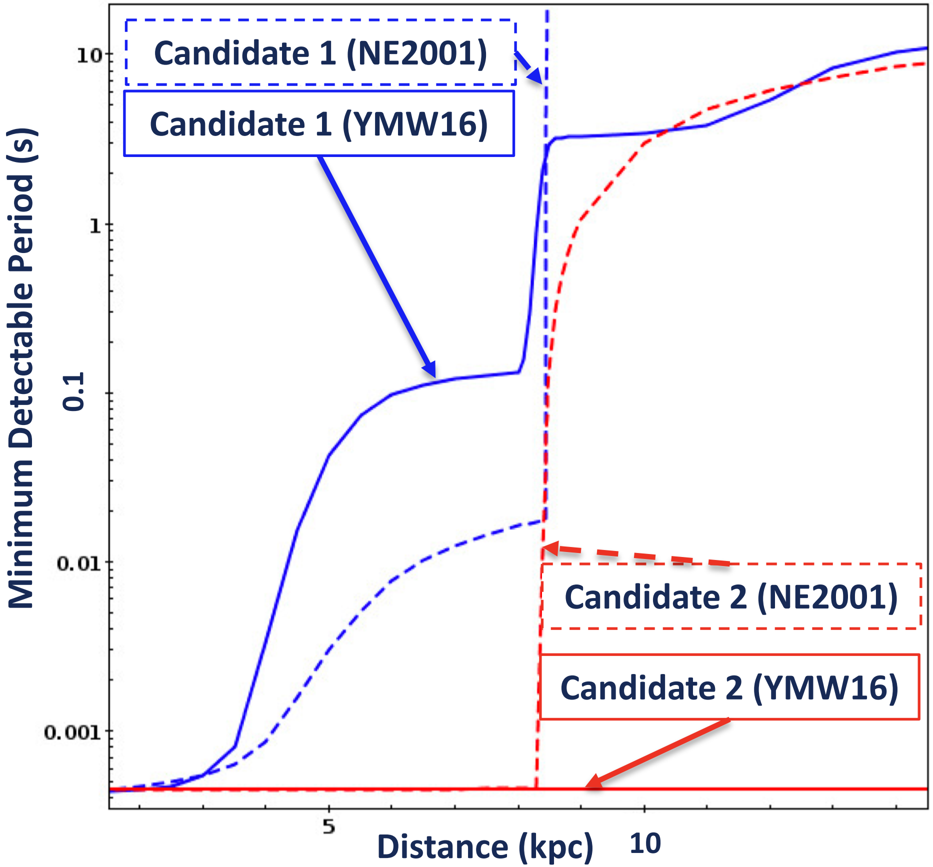
- No pulsations found in GBT S- and C-band pulsation searches
- For steepest sources, **cannot** be radio galaxies
- From YM16 (Yao et al. 2017) & NE2001 (Cordes & Lazio 2002) models, ***if they are PSRs, they must be distant and fast!***



Expect *no* RGs in our sample with $\alpha < -1.8$

What does this tell us?

- Assuming some of these must be PSRs
  - Can't be magnetars, even at the GC
  - Can't be normal PSRs closer than 8 kpc
  - **Most likely MSPs ≥ 4.5 kpc**
- Constraints weaker if scattering screen is foreground (Bower et al. 2014)



Polarization

- Remaining weapon: Polarization
  - Polarization would strengthen case for PSRs
  - Faraday Rotation of the magnetar, 3” from Sgr A*, is largest of any known PSR
  - High Faraday Rotation would be smoking gun that candidates are PSRs at the GC
  - Lack of high Faraday Rotation inconclusive – other known GC PSRs have lower Faraday Rotation
- Work in progress: Weak polarization limit on one candidate from non-optimized serendipitous data – other efforts underway

On-going and Next Steps

- Parallel project: High resolution radio imaging of Fermi unidentified sources---If compact & steep => radio & high-energy timing (e.g., Arzoumanian et al. 2011)
- For radio-based searches - what can we do?
  - L band: combination of scattering and RFI likely killed us
  - C band: insufficient sensitivity (steep spectra) likely killed us
- Need much deeper and/or cleaner observations (Marthi et al. 2011)

Subset MUST be GC MSPs!

μGMRT at L band?