Parsec-scale Constraints on the ISM From the Millisecond Pulsars in *Terzan5*

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Clusters of ancient stars (9-12 billion years old) that orbit our galaxy

Contain $10^5$-$10^6$ stars, many of which have binary companions

Very high densities (100-10,000 stars/ly$^3$) result in stellar encounters and collisions!

They are effectively millisecond pulsar factories (and strange ones at that!)

Number known has more than tripled in the last 6 yrs
Total number of globular cluster pulsars = 128

<table>
<thead>
<tr>
<th>Telescope</th>
<th>PSRs</th>
</tr>
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<tbody>
<tr>
<td>Jodrell Bank</td>
<td>5</td>
</tr>
<tr>
<td>Parkes</td>
<td>39</td>
</tr>
<tr>
<td>Arecibo</td>
<td>27</td>
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<tr>
<td>GBT</td>
<td>56</td>
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<td>GMRT</td>
<td>1</td>
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</tbody>
</table>
Terzan 5

- Very massive cluster with a high central density
- Verbunt and Hut (1987) calculated that it had one of the highest interaction rates of any cluster
- Distance ~ $8.5 \pm 2$ kpc (Cohn et al. 2001)
- Within ~ 1 kpc of Galactic center $(l,b) = (3.8^\circ, 1.7^\circ)$
- Interstellar electrons (i.e. Dispersion Measure or DM) make deep searches quite difficult (e.g. scattering and smearing)

Deep VLA observations by Fruchter and Goss (1990, 2000) found point sources and ~ 2 mJy of diffuse emission in core: 60-200 MSPs?

- From 1990-2001, though, only 3 MSPs were discovered
33 Millisecond Pulsars in Terzan 5!
(First 21 reported in Ransom et al., 2005, Science, 307, 802)
New Timing Solutions

- All of the science comes from pulsar timing!
- Currently have timing solutions for 32 of the 33 pulsars
- **Typical position errors:**
  - ~0.01" in RA
  - ~0.1-0.4" in DEC
- Period derivatives show that ~half of the pulsars are on the back side of the cluster
De-Dispersion

- Lower frequency radio waves are delayed with respect to higher frequency radio waves by the ionized interstellar medium ($\Delta t \propto DM \nu^{-2}$) (DM = Dispersion Measure)
- The amount (i.e. the DM) is unknown for each location in the galaxy and is determined by the total number of electrons between us and the location
- We must search over different possible DMs
Ter5 DM Distribution

- DM range from \(~234\text{-}244\text{ pc/cm}^3\), all due to ISM
- Constrains the distance to Ter5 (argues for < 8 kpc)
- This implies a steep gradient in electrons (0.17 pc/cm³/arcsec) across only a couple arcminutes of sky
- But positions show that things are quite complicated...
- New constraints on ISM structure on (projected) scales of \(~0.01\text{-}4\text{ pc}\)
**DM Structure Function:** \( D_{DM}(\delta\theta) \)

(See Cordes 2005, unpublished)

- Related to phase structure function by: \( DM = -\frac{\delta\phi}{\lambda r_e} \)

\[
D_{DM}(\delta\theta) = \left( \frac{1}{\lambda r_e} \right)^2 D_\phi (b = 0, \tau = 0, \delta r_s = d\delta\theta)
\]

- With \( \delta\theta \ll 1, \alpha = \beta - 2 = 5/3, SM = C_n^2 d_{\text{eff}}, \) and \( C_n^2 \sim \text{const} \)

\[
D_{DM}(\delta\theta) = 0.453 \, (\text{pc cm}^{-3})^2 \left( \frac{d_{\text{eff}}}{d} \right) SM(d_{\text{eff}}\delta\theta)^\alpha
\]

(DM in pc cm\(^{-3}\), d in kpc, SM in kpc m\(^{-20/3}\), \( \delta\theta \) in arcsec)

- Compute \((\Delta DM)^2\) for all MSP baselines: \( n(n-1)/2 = 496 \)

- MSP separations \( \delta\theta = 0.3'' - 98'' \)
  - At \( D = 8.5 \) kpc, that is \( r = 0.01-4 \) pc
  - Spatial wavenumber (\( q=1/r \)) \( q = 2\times10^{-15} - 9\times10^{-17} \) m\(^{-1}\)
\[ \alpha = \frac{5}{3} \]
\[ \alpha = 1.41 \pm 0.13 \]
Interpreting the measurements...

\[ D_{DM}(\delta \theta) = 0.453 \left( \text{pc cm}^{-3} \right)^2 \left( \frac{d_{\text{eff}}}{d} \right) \text{SM}(d_{\text{eff}} \delta \theta)^\alpha \]

For Ter5, \( d_{\text{eff}} \sim d \), and we can solve for SM:

\[ \text{SM}_{\text{DMvar}} \sim 0.20 \text{ kpc m}^{-20/3} \]

**NE2001**
(Cordes & Lazio 2003):

\[ \text{SM}_D \sim 0.80 \text{ kpc m}^{-20/3} \]
\[ \text{SM}_{\text{DM}} \sim 0.29 \text{ kpc m}^{-20/3} \]

**Pulse Broadening**
(Nice & Thorsett 1992):

\[ \text{SM}_\tau \sim 0.034 \text{ kpc m}^{-20/3} \]

Since \( \text{SM} = C_n^2 d_{\text{eff}} \),

\[ C_n^2 \sim 0.023 \text{ m}^{-20/3} \]
Outlook for the future...

- Recent surveys have found 4+ pulsars in several bulge globular clusters (M28, NGC6440, NGC6440). DM variations in each should be mostly due to ISM.

- Temporal DM variations from the bulge clusters will be nearly impossible in the short term, however, many MSPs have been found in closer non-bulge clusters (M5, M15, M71, M30...)

- Longer term, an “Arecibo in the South” would find and time hundreds of new cluster MSPs... (Chinese FAST?)