Hittin' the Millisecond Pulsar Jackpot in Globular Cluster Terzan 5

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Summary

We report the discovery of 21 millisecond pulsars (MSPs) in the rich globular cluster Terzan 5 using the Green Bank Telescope at 2 GHz. This cluster, located near the galactic center, has long been suspected of harboring many MSPs due both to its large predicted stellar interaction rate [1] and the steep-spectrum radio emission observed in its core [2]. However, earlier but extensive pulsar searches using the Parkes radio-telescope had only uncovered 3 pulsars [3,4,5], due partly to the deleterious effects of the ISM towards the cluster.

Our 6-hr observation of Terzan 5 in July 2004 taken with the GBT, the S-band receiver and the Pulsar Spigot [6] (giving us 600 MHz of usable bandwidth) was 5-10 times more sensitive to MSPs than the Parkes searches, and resulted in 14 new MSPs, while follow-up observations provided 7 others. Terzan 5 now has more known pulsars (24) than any other globular cluster in the Galaxy, confirming that it is (or was) one of the largest producers of MSPs [7,8].

At least 13 of the new pulsars are members of binary systems. There are two or more eclipsing systems (one of which, Ter5P, likely has a peculiar evolved companion), the 3rd and 4th fastest known rotators (at P_{psr} = 1.67 and 1.73 ms they are the fastest MSPs known in globular clusters), a rare long orbital period (P_{orb}~60 days) cluster binary, and two highly eccentric binaries. The relativistic periastron advance for the two eccentric systems indicates that they both likely have massive pulsars. More quantitatively, at least one of these pulsars has a mass >1.68 $M_\odot$ at 95% confidence. Such large neutron star masses constrain the equation of state of matter at or beyond the nuclear equilibrium density [9].

Observations of the cluster over the next year or two will provide a precise mass for one of the seemingly massive MSPs, will probe the mass-to-light ratio of the cluster core (and provide evidence for or against a black hole residing there), and the mass distribution of the cluster as projected on the sky, will establish precise positions (<1") of the pulsars for future IR and X-ray observations, and will undoubtedly uncover additional MSPs.

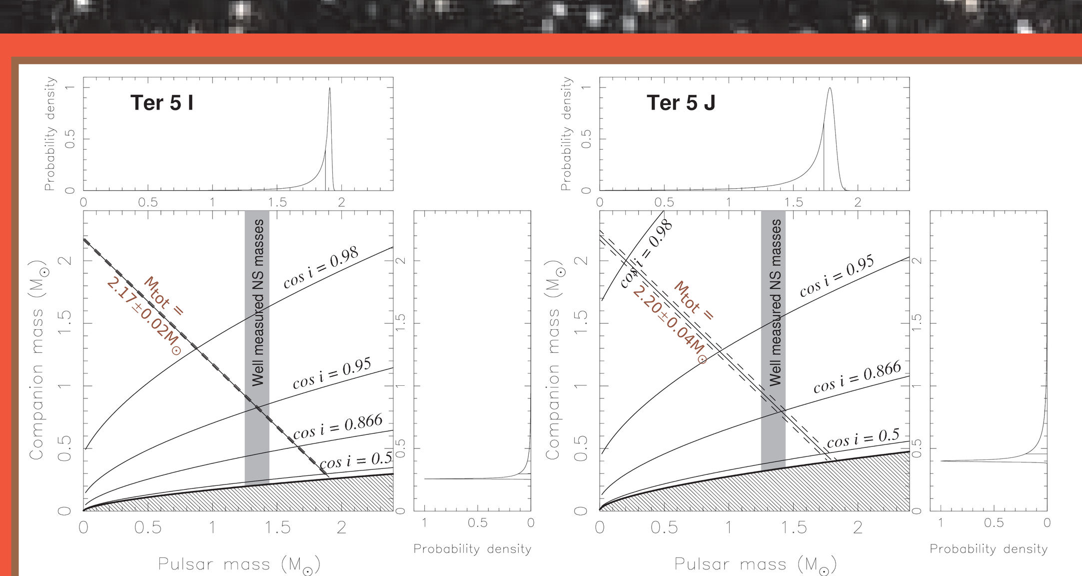
Terzan5's Pulsars

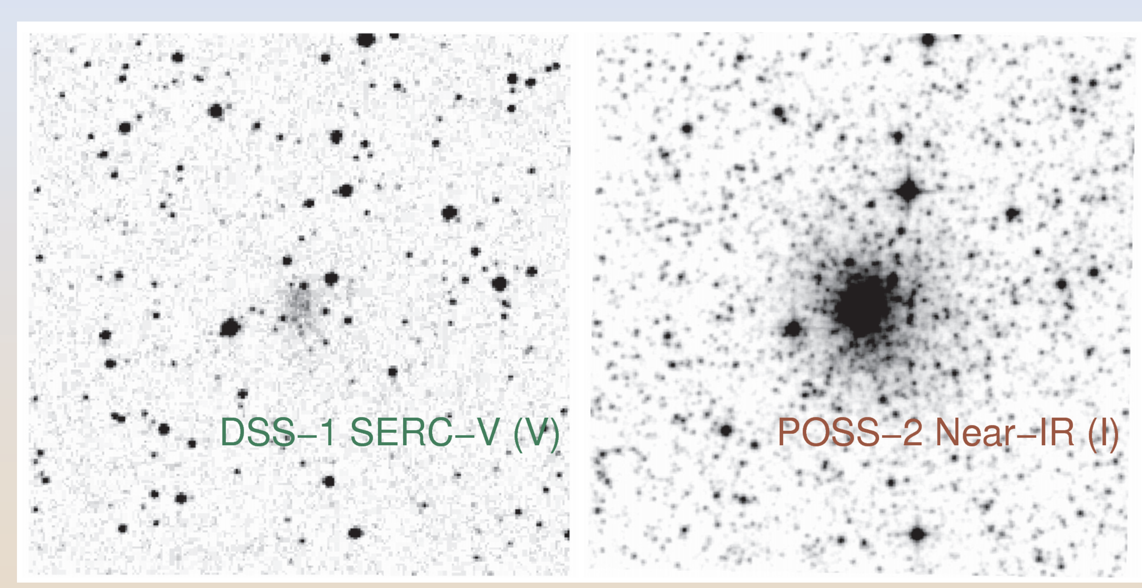
The 1950 MHz GBT+Spigot pulse profiles for the pulsars known in Terzan 5. All but Ter5A, C, and D [3,4,5] (in the orange rectangle) are newly discovered. Each profile is the weighted average of the best detections of that pulsar and is a measure of the relative flux density as a function of rotational phase. Asterisks indicate that the pulsar is in a binary system, and the length of the horizontal error bar (0.3 ms) is the effective system time resolution.

PSR	P_{psr} (ms)	Dispersion Measure (pc cm^{-3})	1950 MHz Flux Density (μJy)	P_{orb} (days)	x (lt-s)	Eccentricity	Minimum m_2 ($M_\odot$)
A^e	11.56315	242.44	1020	0.0756	0.120	0	0.089
C	8.43610	237.14	360				
D	4.71398	243.83	41				
E	2.19780	236.84	48	60.06	23.6	~0.02	0.22
F	5.54014	239.18	35				
G	21.67187	237.57	15				
H	4.92589	238.13	15				
I	9.57019	238.73	29	1.328	1.818	0.428	0.24
J	80.33793	234.35	19	1.102	2.454	0.350	0.38
K	2.96965	234.81	40				
L	2.24470	237.74	41				
M	3.56957	238.65	33	0.4431	0.596	0	0.14
N	8.66690	238.47	55	0.3855	1.619	0.000045	0.48
O^e	1.67663	236.38	120	0.2595	0.112	0	0.036
P^e	1.72862	238.79	77	0.3626	1.272	0	0.38
Q	2.812	234.50	27	>1?	Unk.	Unk.	Unk.
R	5.02854	237.60	12				
S	6.11664	236.26	18				
T	7.08491	237.70	20				
U	3.289	235.50	16	>1?	Unk.	Unk.	Unk.
V	2.07251	239.11	71	0.5036	0.567	0	0.12
W	4.20518	239.14	22	4.877	5.869	0.015	0.30
X	2.999	240.03	18	>1?	Unk.	Unk.	Unk.
Y	2.04816	239.11	16	1.17	1.16	0	0.14

Table 1: Known pulsars in Terzan 5. Pulsars listed without orbital parameters are likely isolated systems while those marked with an ^{e} are eclipsing systems. The errors on the dispersion measures (DMs) range from 0.01–0.1 pc cm^{-3} and the errors on the measured flux densities are ~30%. The flux densities for the eclipsing pulsars include only the times when the pulsar is not eclipsed. The light travel time across the projected pulsar semi-major axis is defined as $x \equiv a_1 \sin(i)/c$. Eccentricities listed as "0" are too small to measure at present and have been set to zero for orbital parameter fitting. The minimum companion mass m_2 was calculated assuming a pulsar mass m_1 of 1.4 $M_\odot$ and i=90° except for Ter 5 I and J. All measured parameters were determined using the TEMPO software package.

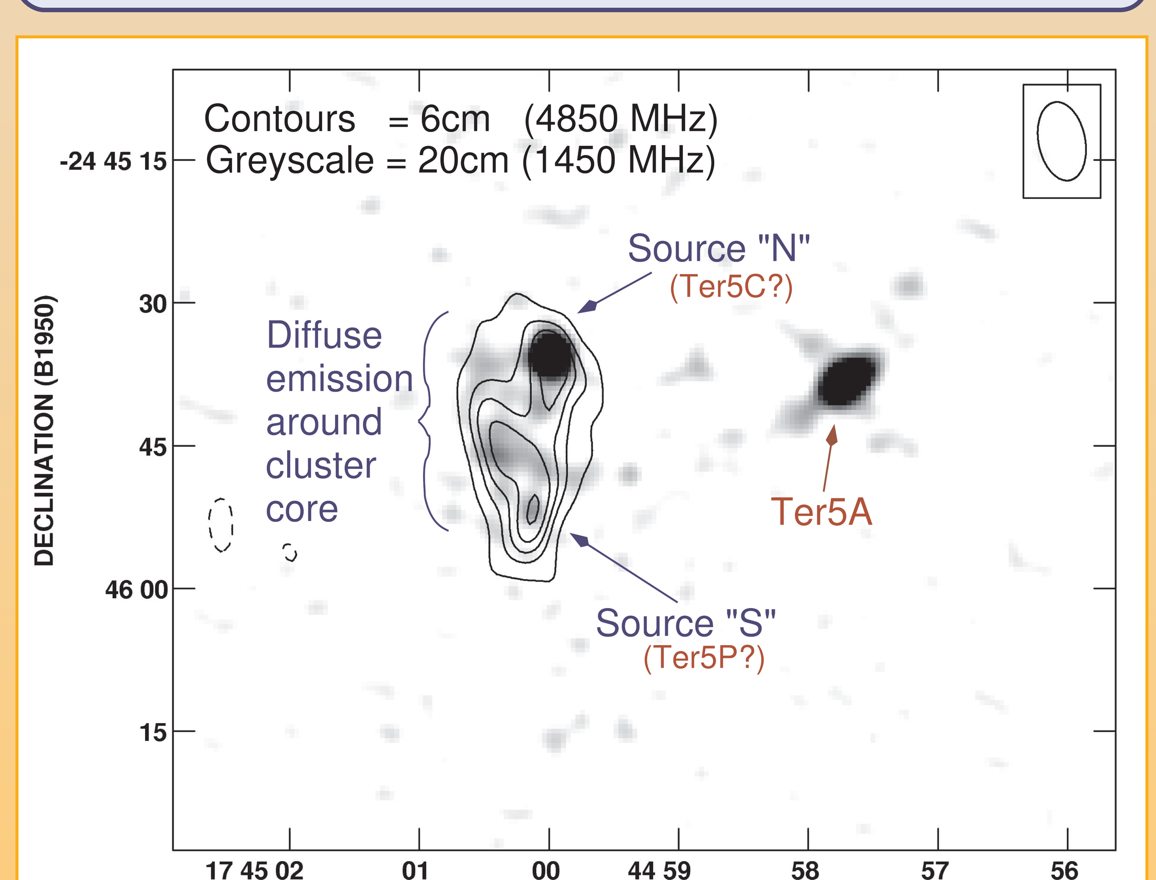
Ter5I and J





Terzan 5

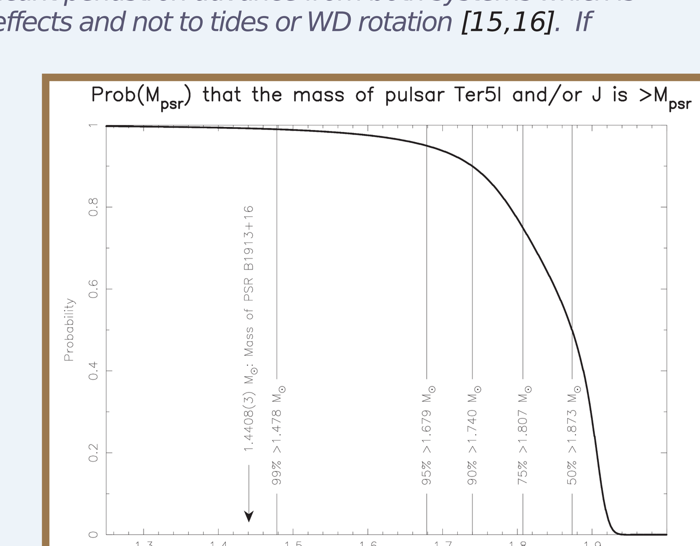
Terzan 5 is one of the richest globular clusters in the Galaxy. It has near solar metallicity [10] and lies within ~1 kpc of the Galactic center [D=8.7±2 kpc and (l,b)=(3.8°, 1.7°)] [11], which contributes to its high obscuration (A_V~7.7, above) and dispersion measure (DM~240 pc cm^{-3}). Its large mass and very high core density (10^5-10^6 $L_\odot$ pc^{-3}) have led to predictions that the stellar interaction rate in its core is one of the largest of all Milky Way globular clusters [1] and therefore, perhaps, also its population of MSPs [7,8]. A known LMXB and ~10 additional X-ray sources support the idea of a high interaction rate [12]. Deep radio images of Terzan 5, which are not affected by the dispersive effects of the ISM, were made with the Very Large Array and showed what appeared to be several radio point sources as well as the integrated emission from many tens or even hundreds of pulsars with low flux densities (below) [2].



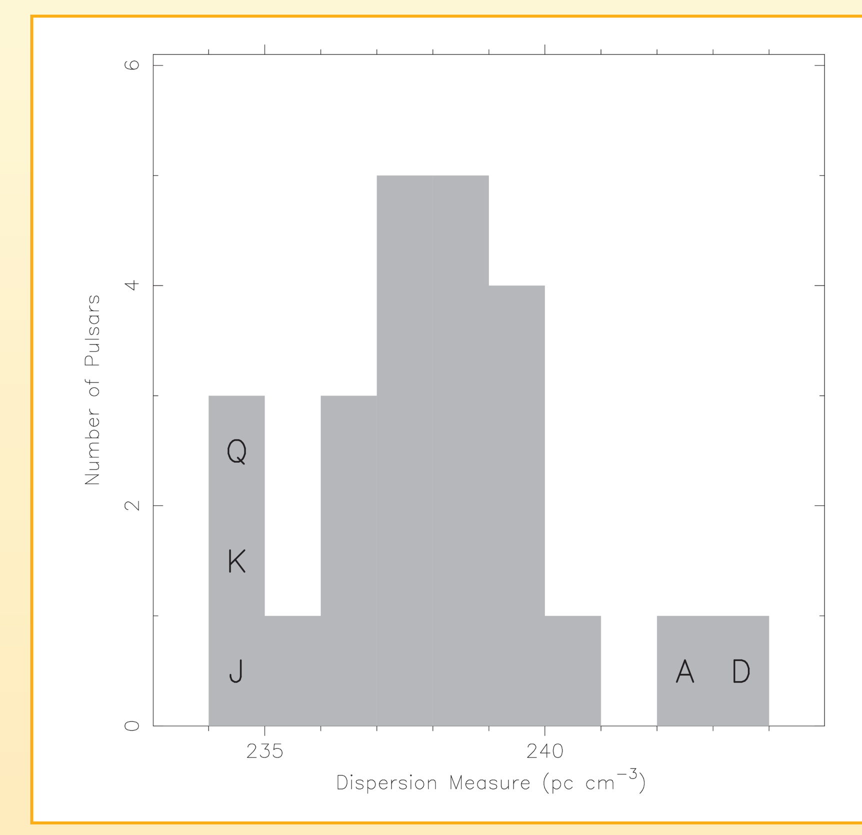
Massive Neutron Stars in Terzan 5

Two of the pulsars, Ter5I and J, are in compact orbits around what are almost certainly white dwarfs (WDs). Unlike most MSP-WD binaries which have circular orbits from the "recycling" process, these systems have highly eccentric orbits and were therefore formed in a different manner. A likely formation mechanism involves the direct collision between an isolated neutron star (NS) and a red giant [14]. After a short period of possibly hypercritical accretion and the ejection of most of the envelope, the resulting system would include a mildly recycled pulsar, a 0.2-0.4 $M_\odot$ "WD" companion, and an eccentric orbit - exactly what we observe in these two systems.

We have measured highly significant periastron advance from both systems which is likely due to general relativistic effects and not to tides or WD rotation [15,16]. If correct, GR provides the total system masses (left), which combined with the mass function and a random orbital inclination (i) distribution allow us to calculate marginal probability distributions for the pulsar and companion masses. For both systems, the median pulsar mass is >1.7 $M_\odot$, considerably more massive than the NSs that have been well measured to date. Calculation of the joint probability that at least one pulsar has a mass >M_{psr} leads to more stringent limits (right).

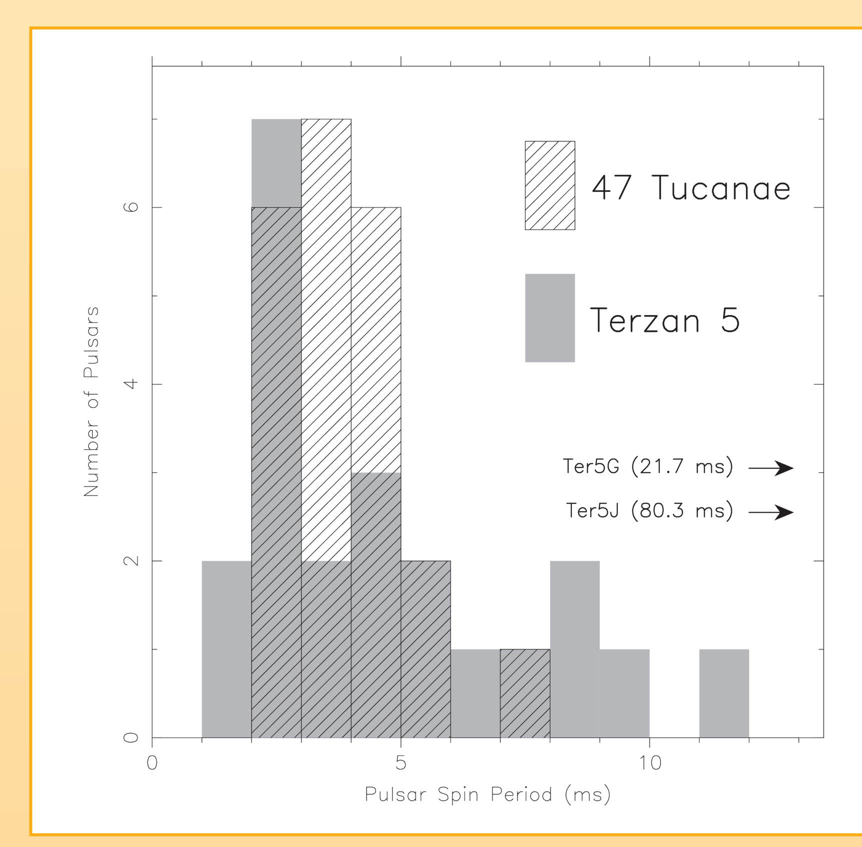


Ter5's Pulsar Population



Dispersion Measure (DM) Distribution

A histogram of the DMs for the 24 known pulsars in Terzan 5. The letters indicate pulsars with "outlying" DMs, of which only Ter5A currently has a precisely determined position (36" away from the cluster center). The pulsars with "central" DMs are almost certainly located very near the cluster core on the sky. The total spread in DM is the largest known for any globular cluster.



Spin Period Distribution

A histogram of the spin periods of the 24 pulsars known in Terzan 5 (solid grey) and the 22 pulsars known in 47 Tucanae (hashed). The 47 Tuc pulsars are a homogeneous population with periods 2.1-7.6 ms [13], while those in Terzan 5 have a flatter distribution that includes six pulsars slower than 7.6 ms and the four fastest pulsars known in GCs (P_{psr} = 1.67, 1.73, 2.05, and 2.07 ms). A Kolmogorov-Smirnov test suggests that these samples are drawn from different parent distributions at 85% confidence. These differences may be related to the dynamical states of the cluster cores (i.e. just pre- or just post-core collapse for Terzan 5 [11]), different epochs of MSP creation, or the occurrence of unusual evolutionary mechanisms that only manifest themselves at very high (i.e. >10^5 pc^{-3}) stellar densities.

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The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. JWTH is an NSERC PGS-D fellow. IHS holds an NSERC UFA and is partially supported by an NSERC Discovery grant. FC thanks support from the NSF. VMK holds a Canada Research Chair and is supported by an NSERC Discovery Grant and Steacie Fellowship Supplement, by the FQRNT and CIAR, and by a New Opportunities Grant from the Canada Foundation for Innovation. DLK is a Pappalardo Fellow.