MAD Science Demonstration Proposal

Hunting for optical companions to binary MSPs in Terzan 5

Investigators	Institute	EMAIL
Francesco R. Ferraro	Univ. Bologna (Italy)	francesco.ferraro3@unibo.it
Elena Valenti	ESO - Chile	evalenti@eso.org
Barbara Lanzoni	Univ. Bologna (Italy)	barbara.lanzoni@oabo.inaf.it
Giacomo Beccari	Univ. Bologna (Italy)	giacomo.beccari@oabo.inaf.it
Gabriele Cocozza	Univ. Bologna (Italy)	gabriele.cocozza@studio.unibo.it
Emanuele Dalessandro	Univ. Bologna (Italy)	emanuele.dalessandr2@unibo.it
Scott Ransom	NRAO - (USA)	sransom@nrao.edu
Robert T. Rood	Univ of Virginia - (USA)	rtr@virginia.edu

Abstract:

We propose deep MAD observations to search for optical companions to the known binary Millisecond Pulsars (MSPs) in the highly reddened Globular Cluster (GC) Terzan 5. The optical identification of MSP companions is crucial for unveiling the formation, evolution and recycling process of pulsars. In addition, since most of MSPs are formed via stellar interactions, determining the nature and photometric properties of their companions places significant constraints on the dynamical processes acting in GCs and their impact on the (otherwise normal) stellar evolution. Remarkably, the study of binary MSPs has also an intrisic importance for fundamental physics, since it offers the opportunity to constrain the equation of state of matter at nuclear density. Only 6 optical counterparts to binary MSP companions are known to date in the entire Galactic GC system, and 3 of them have been discovered by our group. The proposed MAD observations could easily double/triple the existing sample. Indeed, among the GCs in which MSP have been detected, Terzan 5 is by far the most surprising: it hosts the largest MSP population (33 objects) of any GC, thus comprising roughly 25% of the known GC MSPs! Even more interesting, 17 of them are in binary systems and 15 are located within a $1' \times 1'$ region, corresponding to the MAD field of view. Hence, this cluster represents the ideal target in which to search for MSP companions and to fully exploit the exceptional capabilities of MAD. The potential return in knowledge of the physics of the degenerate matter is really huge.

Scientific Case:

Globular Clusters (GCs) are very efficient “kilns” for generating exotic objects, such as millisecond pulsars (MSPs), low-mass X-ray binaries, blue straggler stars, etc. MSPs are formed in binary systems containing a neutron star (NS) which is eventually spun up through mass accretion from the evolving companion. The final stage of this *recycling* process is either the core of a peeled star (generally a Helium white dwarf, He-WD) or a very light ($0.01 - 0.03 M_\odot$) remnant of a main sequence (MS) star, orbiting a very rapidly rotating NS (a MSP). Even though the disk of the Galaxy has a total mass 100 times larger than the Galactic GC system, more than 50% of the entire MSP population has been found in the latter. This is not surprising because in the Galactic field the only viable formation channel for MSPs is the evolution of primordial binaries, while in the ultra-dense cores of GCs, dynamical interactions can form various kinds of binaries suitable for recycling NSs into MSPs. Hence, these objects are valuable probes of the cluster dynamics and its impact on the (otherwise normal) stellar evolution. Of course, the optical identification of the companion stars is crucial. In fact, once identified, their photometric and spectroscopic follow-ups allow to unveil their nature and determine their physical parameters, thus leading, in turn, to an improved understanding of the MSP formation mechanisms. For example, the careful examination of the companion light curve (i.e. the optical variations induced by ellipsoidal distortions or irradiation by the pulsar flux) may allow one to constrain the orbital parameters of the system and to investigate the effects of the radiation flux of the MSP onto the companion surface.

Moreover, the possibility to derive the mass ratio of the system from the velocity curve of the companion leads to a direct estimate of the pulsar mass and, in turn, allows to constrain the predictions of the maximum NS mass by different equations of state: hence, binary MSPs also represent a real laboratory for fundamental physics. In this framework, we initiated a long-term program devoted to the systematic search for optical counterparts to MSP companions in GCs. This project has produced a number of discoveries. In particular, of the six optical counterparts to MSPs which have been firmly identified to date in five GCs, three have been discovered by our group and they all turned out to be quite suprising objects: **(1)** In NGC 6397 the optical companion (COM6397A) to the MSP NGC6397A is not a He-WD (as expected by the canonical recycling scenario), but a tidally deformed star (Ferraro et al. 2001, ApJ, 561, L93). **(2)** In the outskirts of NGC 6752 we have identified the companion star (a He-WD; Ferraro et al. 2003, ApJ, 596, L211) to PSR J1911-5958A, the most off–center pulsar ever found in any GC. Colpi et al. (2003, ApJ, 599, 1260) suggested that this object might have been ejected from the core of the cluster by an interaction with a binary black hole. **(3)** A relatively bright star has been found nearly coincident with the nominal position of the eclipsing MSP PSR J1701−3006B in the GC NGC 6266 (Cocozza et al. 2008, ApJ, 679, L105). This objects is photometrically similar to COM6397A, though its radius seems to exceed the Roche Lobe for the system.
Given the diversity of the known companions, enlarging the sample of these exotic objects is an obvious priority. Particularly interesting are the following classes of systems:
• *Eclipsing MSPs with relatively massive companions ($M_c = 0.1$–$0.4\,M_\odot$)* - This growing class of objects is *peculiar to GCs*. King et al. (2003, MNRAS, 345, 678) suggested that most of the current companions to eclipsing pulsars in GCs would be the swollen descendants of MS-TO stars which replaced the original WD companion of the pulsar in an exchange interaction in the cluster core. In particular, Burderi et al. (2002, ApJ, 574, 325) suggested that the anomalous position in the Color Magnitude Diagram (CMD) of COM6397A is consistent with the evolution of an evolved Sub Giant Branch star orbiting the NS and losing mass. This stage should be relatively short, as the MSP companion evolves to become a He-WD. Thus, the identification of optical counterparts along a similar evolutionary path would significantly improve our knowledge of the pre He-WD evolution of MSP companions. Moreover, the frequency of such systems *vs* He-WD MSP binaries would set the relative evolutionary time-scale. A number of MSPs with radio properties similar to NGC6397A have been discovered in Terzan 5 (pulsars P, A and ad).

• *Supermassive MSPs* - The measure of the orbital precession in a few binary eccentric MSPs has led to quite surprising results. If this effect is due to general relativity, the total mass of the system can be derived and the pular mass can be estimated. In a growing number of cases the pulsar mass seems to be larger than $1.44\,M_\odot$, spanning a wide range (at least a factor of two) of values. Two MSPs in Terzan 5 (Ter5I, and Ter5J) show this effect and the estimated pulsar mass is $1.7\,M_\odot$. Such an extra mass is possibly acquired by the NS during the accretion process that transforms the NS into a MSP. Determining the nature of the companions and empirically estimating their masses (through comparison of their position in the CMD with the prediction of stellar evolution models) would further constrain the pulsar mass and give new information on: *(i)* the equation of state of the degenerate matter; *(ii)* the amount of mass that a NS needs to accrete in order to become a MSP, and *(iii)* the stability (and formation process) of supermassive NSs.

Targets and integration time

The discussion above clearly demonstrates that the optical identification of the companion stars to binary MSPs is a crucial step for understanding the evolutionary and recycling mechanisms of pulsars, for a deeper insight on the cluster dynamics, as well as for fundamental physics. If these objects are similar to COM6397A, optical modulation at the orbital period is also expected, providing an additional signature for the correct identification of the counterpart.

Here we present a program which exploits the potential of the MAD system to probe the nature of the companion stars to 15 (out of a total of 17) binary MSPs in Terzan 5, the Galactic GC with the largest known number of MSPs. For all the selected targets we have obtained high-precision radio-timing positions: they are all located within the MAD FoV ($1' \times 1'$) and within the asterism for the AO-correction which has been selected according to the MAD User Manual. Thus, by taking full advantage of the large FoV of MAD and by pushing its performances down to $J = 24$, the proposed observations guarantee the optical identification of most of the target MSP companions, by probing the entire extention of the MS down to $M = 0.1\ M_{\odot}$ and most of the He-WD cooling sequence extention. Indeed, some targets are very promising: for example, among the MSPs which show eclipses in the radio signal (pulsars A, P, O, ad), Ter5P and Ter5ad show long duration eclipses ($\sim 40 - 50\%$ of the period) and several significant orbital frequency derivatives. In both cases this suggests an eclipsing region of several solar radii in size, i.e. a companion which likely is a bloated MS-TO star possibly still filling its Roche Lobe and losing mass, similar to COM6397A (with which they also share a strong X-ray emission). Ter5ad (the fastest-spinning NS ever found, with a period of 1.39 ms) is particularly interesting. Since its radius has been recently estimated to be ≤ 16 Km (Hessels et al. 2006, Science, 311, 1901), the empirical determination of the pulsar mass would critically constrain the equation of state of matter at nuclear densities and the mass-radius relation for NS, which is still unknown. In addition, the properties of Ter5P would suggest that the pulsar is dumping a lot of energy into the companion star, so that irradiation could increase the companion star's brightness making it a more likely target for optical/IR detection.

Note that MAD is the ideal instrument to carry out this project since: *i)* the target field is very crowded and high spatial resolution is therefore mandatory to avoid confusion; *ii)* Terzan 5 is heavily absorbed ($A_V \simeq 7.4$), so that near-IR observations are needed; *iii)* the MSP companions are faint stars (possibily MS and He-WD), so that very deep photometry ($J = 24$, $K = 22$) is required and diffraction limited observations are essential. Finally, because of the need of accurate and deep photometry over a moderate--large field, MAD is superior to NACO. The small FoV of NACO would make the observations less efficient. Moreover, MAD data taken during previous science verification runs (see Bono et al. 2008, astro-ph/0803.2207), clearly show that the use of 3 reference stars for real time correction to the atmospheric turbulence not only provides a wide AO-corrected FoV, but it also allows an easier (with respect to the NAOS-CONICA) and more accurate modeling of the PSF as a function of the star position in the array. The proposed observations should easily double/triple the existing number of known MSP companion stars, thus allowing the first meaningful study of the phenomena driving the formation and evolution of binary MSPs in GCs.

Target	**RA**	**DEC**	**Filter**	**Magnitudes**	**Total integration time** (sec)	**Field** (arcmin)
Terzan 5	17 48 04.068	-24 46 57.22	J	J=15 - 24	11000	1
Terzan 5	17 48 04.068	-24 46 57.22	K	K=13 - 22	11000	1

Guide stars list and positions

The properties of the three stars chosen as guide stars are listed in the Table below. We are aware that the magnitude of the star named GS3 represents the limit *"exceptionally considered"* for the AO stars (see User Manual, § 5), but given the difficulty in finding a good bright asterism in V band in such highly reddened environment, we agree on a degradation of the typical correction performance.

Target: NGC 1111			
	RA$''_{rel}$	**DEC**$''_{rel}$	**V Mag**
GS1	60.3	-5.3	11.3
GS2	-11.3	29.9	12.3
GS3	20.1	42.7	13

Time Justification:

Using the ISAAC ETC Version 3.2.1 with a $0.1''$ seeing and 1.2 airmass, and adopting DIT$\sim$ 5 s to avoid severe saturation of the bright giants and array persistence problem, 5500 s are required to get S/N$\sim$25 both at $J = 24$ and $K = 22$. For background subtraction purpose we need to spend the same amount of requested time on sky positions, since the proposed target is too crowded to perform a jittering technique. Hence we apply for a total integration time (object + sky) of $\sim$ 3 h in each band. Following the instructions listed in the MAD User Manual, we estimate a total amount of $\sim$ 7000 s of overheads in each band. The total time (acquisition + science exposure + overheads) required to completed the project is **10 h**.