Detecting X-ray pulses from millisecond pulsars in the globular cluster 47 Tuc

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1. Abstract

We propose to observe the Galactic globular cluster 47 Tucanae with the pn in timing mode to detect the pulsations from the eight brightest millisecond pulsars in this cluster. This will double the number of millisecond pulsars for which radio and X-ray phase-folded lightcurves exist. *XMM-Newton* is the only observatory with sufficient collecting area and high enough timing resolution to detect these pulsars and to obtain lightcurves of these faint objects. We will use the absolute phase folded lightcurves to discriminate between differing models for the high energy emission such as the polar cap, slot gap or outer gap models. These data will also allow us to examine how the magnetic field evolves when millisecond pulsars are formed.

2. Description of the proposed program

A) Scientific Rationale:

Globular clusters: It is expected that globular clusters (GCs) should contain many binary systems and their products, due to interactions occurring within them (e.g. Di Stefano & Rappaport 1994). These systems *could* play a critical role in the dynamical evolution of GCs, serving as an internal energy source which counters the tendency of GC cores to collapse (see Hut et al 1992 for a review). However, these binaries (and their products) are extremely difficult to locate using traditional optical observations, because of over-crowding. It is almost uniquely using X-ray observations that the binaries, which are also visible at high energies, can be located and studied.

Millisecond pulsars: Binary millisecond pulsars (MSPs) are thought to be 'recycled' pulsars. Accretion onto a neutron star from a close companion is believed to transfer angular momentum to the neutron star, spinning it up to periods of milliseconds (Alpar et al., 1982; Radhakrishnan & Srinivasan, 1982). This is strongly supported by both the discovery of a MSP in an X-ray binary system (SAX 1808.4-3658, Wijnands & van de Klis, 1998) and the presence of kilo-Hertz Quasi-Periodic Oscillations in many LMXBs, which have been found to show millisecond pulsation periods (see van der Klis (1998) and references therein). In globular clusters, MSP progenitor binaries can be readily formed from main-sequence binaries by the exchange of a neutron star into the binary (Rasio, Pfahl & Rappaport, 2000) or they may also (in very high-density cluster cores) form from direct two-body tidal capture (Mardling, 1995) or three-body encounters. Thus we should expect to find many MSPs in globular clusters (GCs), which is in fact true, where e.g. 23 known in the central region of the GC 47 Tuc (see Bogdanov et al. 2006 and references therein). Kulkarni & Anderson (1996) also showed that globular clusters produce millisecond pulsars at a rate per unit mass that is up to an order of magnitude greater than in the Galaxy as a whole. However, the result of a MSP being born in a GC, may change its intrinsic properties. Grindlay et al. (2002) found that MSPs in the globular clusters 47 Tuc and NGC 6397 appear to have a less efficient conversion of rotational spin-down energy into soft X-rays than most field MSPs. Grindlay et al. (2002) suggest that an explanation for this discrepancy is the evolutionary path of these MSPs in GCs. Identifying the MSPs will allow us to test whether the MSPs in other GCs also show this anomaly.

How does the magnetic field evolve? Millisecond pulsars are short period (P) pulsars that have long apparent ages and pulsed optical, X-ray, and γ-ray fluxes significantly below those expected for canonical pulsars with similar periods. These millisecond pulsars also have very low spindown rates ($\dot{P}$) and consequently low surface magnetic fields (B_s), as the surface magnetic field is believed to be proportional to $(\dot{P}P)^{0.5}$. What is unclear since the discovery of millisecond pulsars, is how the surface magnetic field can evolve from high values ($\sim10^{11}$-10^{13} G) to lower B_s values of only $\sim10^8$-10^9 G (see the latest version of the ATNF Pulsar Catalog, Hobbs et al., 2004). Several mechanisms have been proposed. Renewed accretion, which is thought to spin up the pulsar, could also bury the magnetic field (Romani, 1990), reducing the strength of the observed field. This method would also systematically increase the neutron star mass. Alternatively Ruderman (1991) proposed that during spin up, the surface magnetic field evolution could mirror changes in the core magnetic field configuration. The strong interaction between the core's superfluid neutrons, arranged into very dense, almost parallel arrays of quantized vortex lines and the magnetized superconducting protons provide the conditions necessary to produce the pulsar's high magnetic field. During spin up the vortex lines would move inwards, 'dragging' the surface magnetic field to the pole of the hemisphere it started in, which would account for both the change in the magnetic field strength and it would imply that this model, known as the 'spin-up squeezed' model would result in a MSP that would have *either* an orthogonal *or* an aligned magnetic field configuration.

More recently, Ruderman (2004) examined the six MSPs for which both X-ray and radio lightcurves were known, to provide evidence to support the theory that recycled MSPs should have mainly orthogonal or aligned magnetic field configurations, which should result if the 'spin-up squeezed' theory for the magnetic field evolution proposed by Ruderman (1991) is correct. Of these six, he concluded that four (PSR B1821-24, PSR B1937+21, PSR J0030+0451, PSR J2124-3358) showed evidence for being orthogonal rotators. The evidence for this assertion was that these four pulsars showed two sub-pulses of comparable strength separated in time by about half a period. PSR J0437-4715 was the only MSP of the six showing a single very broad X-ray lightcurve and is thought to be an almost aligned beam (and dipole moment). The X-ray spectrum is soft, indicative of a heated polar cap, which one would expect to see in an aligned rotator configuration. Many of the MSPs detected in Galactic globular clusters show soft spectra (e.g. Bogdanov et al. 2006), unlike those in field. These pulsars may be aligned rotators, as we do not expect to see a heated polar cap in the orthogonal rotator geometry. This could be further evidence for a different evolutionary process for GC MSPs as opposed to field MSPs.

Where does the high energy emission come from? Of the hundred or so MSPs known (see Hobbs et al., 2004) the large majority have been detected in the radio domain only. Just a dozen of these rotationally powered MSPs have been detected in the X-ray domain. Thermal X-ray emission (between 0.05 and 1 keV) can be from a heated region, most likely the polar cap, which is bombarded by high energy particles that are accelerated in the outer magnetosphere. Non thermal emission, characterised by hard power law spectra that can extend from the X-rays to the γ-rays, is thought to arise from the magnetosphere. Alternatively, the emission can be from a pulsar driven synchrotron nebula or interaction of relativistic pulsar winds with either a wind from a close companion star or the companion star itself. The absolute phase folded lightcurve can also reveal the site of the emission, when compared to the radio and gamma-ray absolute phase folded lightcurves. Alignment of the pulse with the radio pulse indicates emission from the polar cap, whereas its misalignment indicates more of a magnetospheric origin. The width of the pulse also shows the size of the emitting region. Thus we can use X-ray observations to understand both the surface and the environment of the pulsar and eventually to determine unknown quantities, such as the orientation of the magnetic field and the equation of state of the matter at the surface of the neutron star, through modelling of the lightcurve (e.g. Bogdanov & Grindlay 2009).

Several models have been proposed which describe the origin of the high energy emission, the most supported of those being the polar cap model (Daugherty & Harding, 1996), the slot gap model (Arons 1983) and the outer gap model (Cheng, Ho & Ruderman, 1986). In the polar cap models, a rotation-induced electric field is assumed to exist above the polar cap and to accelerate particles to ultra-relativistic energies. These energetic particles initiate pair cascades by radiating gamma-rays (through curvature radiation or inverse Compton scattering), which then decay into pairs in the strong magnetic field. The pair cascade produces an outflowing pair plasma as well as high-energy radiation. Unlike the polar cap model, the outer gap model assumes that acceleration occurs near the light cylinder where the high-energy emission is produced through Compton scattering by particles generated in pair cascades. In the 'hybrid' slot gap model, the vacuum electric field vanishes at the polar cap rim. Close to this boundary the field decreases which necessitates a long distance to accelerate particles to the Lorentz factor needed to radiate photons energetic enough to produce pairs. This results in a region close to the last open field line in which the pairs are formed and from which the high energy emission originates. Due to the lack of observations of MSPs at high energy, it is not clear which of these models ultimately describes the emission mechanisms. For those pulsars with good high energy and radio coverage we observe very disparate lightcurves and spectra as we have simply not yet observed sufficient numbers of pulsars to gain an overall view of their emission profiles and spectra. We will extract X-ray lightcurves for the brightest MSPs to determine what model describes the high energy emission.

The aim of this proposal is to detect the X-ray pulsations from the millisecond pulsars in 47 Tuc. This has never previously been attempted as other satellites lack the necessary characteristics, namely high throughput and very good temporal resolution. 47 Tuc has never been observed with *XMM-Newton* as the high density of X-ray sources in the central regions means that they will be spatially confused. However, our recent work with *Fermi* Large Area Telescope (LAT) (Abdo et al. 2009a) as a part of the *Fermi* LAT collaboration has shown that even though 47 Tuc is detected as a point source with the LAT, using our radio ephemerides we are able to deconvolve the lightcurve and retrieve the pulse profiles for many of the 47 Tuc millisecond pulsars (see Fig. 1). There are only a dozen of the 100 or so known millisecond pulsars (see Hobbs et al., 2004) for which radio and X-ray lightcurves exist. Seven of these now have gamma-ray lightcurves (Abdo et al. 2009b). A single observation of 47 Tuc in X-rays will allow us to double the number of millisecond pulsars for which X-ray, radio and eventually gamma-ray phase-folded (as more photons are accumulated with *Fermi*) lightcurves exist. This is essential for understanding these objects as detailed above.

47 Tuc is the ideal globular cluster for this project, as it is one of the closest globular clusters, at only 4.5 kpc - allowing us to reach a deep luminosity limit for a reasonable amount of observing time, with very low interstellar absorption (1.3×10^{19} cm^2) essential for detecting millisecond pulsars which emit mostly in the soft X-ray domain. As pointed out above, only XMM-Newton has the necessary throughput combined with temporal resolution to carry out such a project. A 130 ks observation with Chandra and the HRC would detect around 40 photons for the brightest 47 Tuc pulsars. Further, 47 Tuc contains 23 known millisecond pulsars (see Bogdanov et al. 2006 and references therein) which means that in a single pointing we are able to observe a large sample. We will also exploit the MOS data (in full frame) to detect and analyse other globular cluster sources that are not spatially confused outside the half mass radius (2.79'), such as cataclysmic variables and active binaries to constrain their population numbers (see e.g. Heinke et al. 2005).

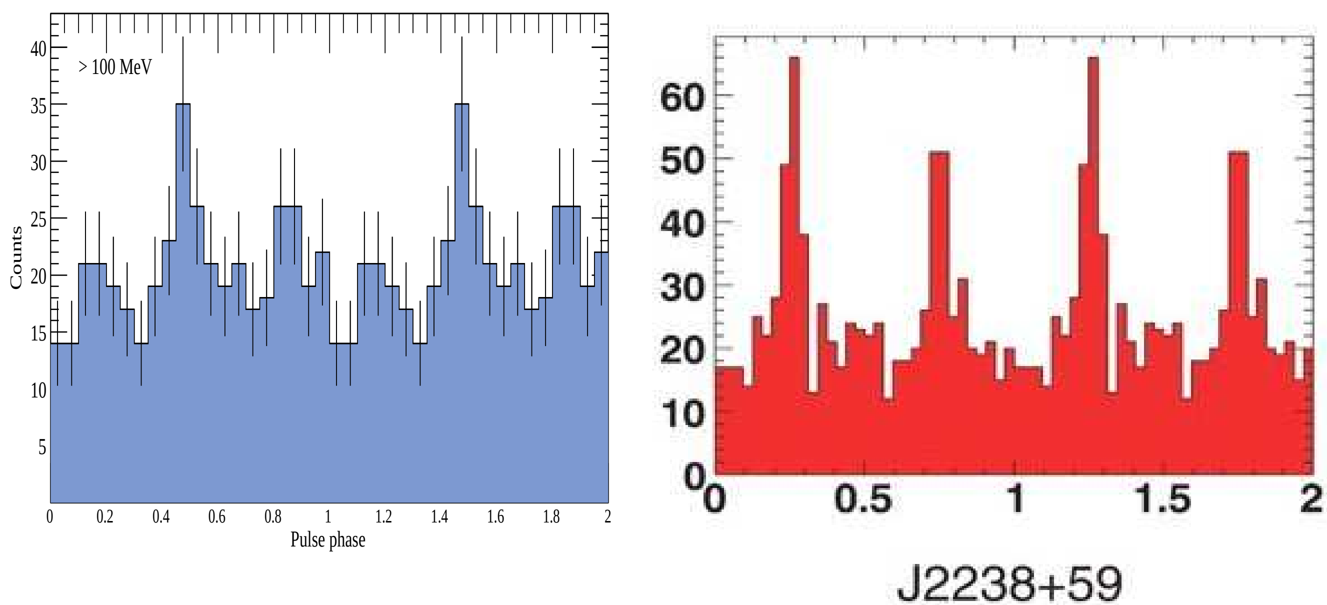

Figure 1: *Left panel*: Preliminary results of 1 of the 47 Tuc's pulsar phase-folded lightcurves from 1 year of Fermi LAT data. *Right panel*: Example of a phase-folded lightcurve of a blind search pulsar found with the Fermi LAT

B) Immediate Objective:

We propose to observe the Galactic globular cluster 47 Tucanae with the pn in timing mode (and the MOS cameras in full frame mode to observe other globular cluster sources outside of the half mass radius (central 2.79' only) to detect the pulsations from the eight brightest millisecond pulsars in this cluster. This will double the number of millisecond pulsars for which radio, X-ray and gamma-ray absolute phase-folded lightcurves exist. This sample will allow us to constrain where the high energy emission is generated in these extreme objects and to allow us to examine how the magnetic field evolves when millisecond pulsars are formed.

3. Justification of requested observing time, feasibility and visibility

We propose to observe the globular cluster 47 Tuc for 130 ks using the pn timing mode and the MOS cameras in full frame. With this we will detect the 8 brightest MSPs with >200 counts, to determine the pulse profile (see Webb, Olive & Barret 2004, Webb et al. 2004, Pancrazi et al. in prep.). 47 Tuc is visible during A09 for 50 orbits for 130 ks. Using the spectral information of each MSP in 47 Tuc (Bogdanov et al. 2006) and WebPIMMS (powered by PIMMS v3.9j), for the pn using the medium filter (to avoid stray light from the brightest stars) for the total PATTERN=0 count rate gives the count rates in Tab. 1.

Table 1: Brightest to faintest MSPs in 47 Tuc for which we will be able to detect pulsations:

Pulsar	Count rate (s^{-1})	Tot. cnts (130ks)
W	0.0044	572
J	0.0034	436
0	0.0030	399
L	0.0025	321
R	0.0020	261
E	0.0017	220
F	0.0015	195
S	0.0015	195

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4. Report on the last use of XMM-Newton data

We have observed 9 Galactic globular clusters obtained from proposals including: *The Stellar Collision Rate and Neutron Star Binaries in Globular Clusters*, D. Barret, (No. 20584); *Further Observations of Large Core Globular Clusters with XMM-Newton*, D. Barret (No. 14845); *XMM-Newton Observations of Large Core Globular Clusters*, D. Barret (No. 8528); *Dim X-ray sources in globular clusters*, M. Turner (No. 11222); *Globular clusters*, M. Watson, (No. 11130). These data have resulted in 8 refereed journals, four invited reviews, 30 conference proceedings and were the subject of two PhDs. We also have multiwavelength (radio/optical/Chandra) follow-up data. We have also observed 10 millisecond pulsars obtained from proposal including: *X-ray emission from millisecond pulsars*, M. Watson, (No. 11110), which have resulted in two A&A papers, and 8 proceedings and are the current subject of a PhD thesis, along with simultaneous radio data. Further we have submitted 6 images of globular clusters to the XMM-Newton Image Gallery.

5. Most relevant applicant's publications

Webb N.A., Barret D. 2007, ApJ, 671, 727 : Constraining the equation of state of supra-nuclear dense matter from XMM-Newton observations of neutron stars in globular clusters

Webb, N. A.; Olive, J.-F.; Barret, D.; et al. 2004, A&A, 419, 269: XMM-Newton spectral and timing analysis of the faint millisecond pulsars PSR J0751+1807 and PSR J1012+5307

Webb, N.A., Olive, J.-F., Barret, D., et al. 2004b, A&A, 419, 269: XMM-Newton spectral and timing observations of the millisecond pulsar PSR J0218+4232

Abdo, A. A., Ackermann, M., Ajello, M., et al., 2009, Science, 325, 848: A Population of Gamma-Ray Millisecond Pulsars Seen with the Fermi Large Area Telescope