XMM-Newton observations of *Fermi* detected pulsars

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1. Abstract

We propose to make *XMM-Newton* observations of six pulsars detected with the *Fermi LAT* to increase the number of pulsars for which good X-ray, gamma-ray and radio data exist in order to constrain the mechanism which generates the pulsar high energy emission. For four of the proposed pulsars this will be the first observation in X-rays. We will use both the spectra and phase-folded lightcurves to discriminate between differing models for the high energy emission such as the polar cap, slot gap or outer gap models. *XMM-Newton* is the only observatory with sufficient collecting area and high enough timing resolution to detect these pulsars and to obtain the spectra and lightcurves, necessary to discriminate between the high energy models.

2. Description of the proposed program

A) Scientific Rationale:

Of the almost 2000 pulsars known (see Hobbs et al., 2004) the large majority have been detected in the radio domain only. Less than 5% of these rotationally powered pulsars have been detected in the soft X-ray domain (Becker 2009). Of those detected in the X-ray domain, and for only 34 of them X-ray pulsations have been detected (Becker 2009). Only seven pulsars were identified in gamma-rays by the high energy instrument *EGRET* aboard the *Compton Gamma Ray Observatory* (CGRO), although it was believed that many of the unidentified objects were also associated with pulsars. The *Fermi Large Area Telescope* (LAT) has already identified more than six times this number in its first year (Abdo et al. 2009a) and has even detected 16 new gamma-ray selected pulsars (Abdo at al. 2009b) and it has detected, for the first time, globular clusters in the hard gamma-ray domain (>100 MeV), where the emission is likely to be due to the integrated contribution of up to 60 millisecond pulsars (Abdo et al. 2009c).

The lack of observations made in the X-ray (and gamma-ray) domain has hampered our understanding of these extreme objects. One of the many open questions in pulsar physics is the origin of their high energy emission. Several models have been proposed which describe the origin of the pulsar high energy emission, the most supported of those being the polar cap model (e.g. Daugherty & Harding, 1996), the slot gap model (e.g. Arons 1983) and the outer gap model (e.g. 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 pulsars 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 propose X-ray observations of six pulsars that have been recently detected in gamma-rays. The information gathered from gamma-ray, X-ray and, where possible, radio will enable us to constrain the site of the emission and hence the emission mechanism.

In the X-ray domain, the pulsar emission is the result of highly accelerated particles in a strongly magnetised environment. Thermal emission can originate from a heated region, most likely the polar cap, which is bombarded by high energy particles or from the surface of the cooling neutron in the case of 'normal' pulsars (not those of the millisecond variety). Non thermal emission, characterised by hard power law spectra, is thought to arise from the magnetosphere. Alternatively, the emission can originate from a pulsar driven synchrotron nebula or from interaction of relativistic pulsar winds with either a wind from a close companion star or with the companion star itself. The phase-folded lightcurve can also reveal the site of the emission, when compared to those in radio and gamma-rays. Alignment of the X-ray 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 study the properties of 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.

The six pulsars that we propose to observe on behalf of the *Fermi* LAT team include two pulsars found in the blind pulsar search for which there are no radio counterparts (see Fig. 1). Three other pulsars have radio counterparts and therefore the position is well known. All of these pulsars have not been observed with XMM-Newton, nor Chandra. J1459-60 has previously been observed with Swift, but with only ~20 counts this is insufficient to create a phase-folded lightcurve. The last pulsar is a millisecond pulsar that has previously been observed using XMM-Newton, but in the full frame mode. Because of the short period (P = 3.2 ms) the pulse profile can not be determined using the full frame data (which has a time resolution of 73.4 ms).

The large field of view of the EPIC full frame is essential to cover the error circle of the blind search pulsars, which has a radius $< 15'$ obtained from the minimisation of the pulse time residuals error radius. *XMM-Newton* is the only observatory with a large enough collecting area and at the same time with a high enough timing resolution, to detect the X-ray counterpart of these six pulsars and to extract the spectra and lightcurves, which will enable us to determine which model better describes their high energy emission. Prior to observations made with *XMM-Newton*, such analyses were impossible, due to the faintness of the majority of pulsars. Moreover, our team has a long, successful, track record in pulsars observations with *XMM-Newton* data, so we will be in a good position to reduce and analyse the data accurately (see sections 4 and 5).

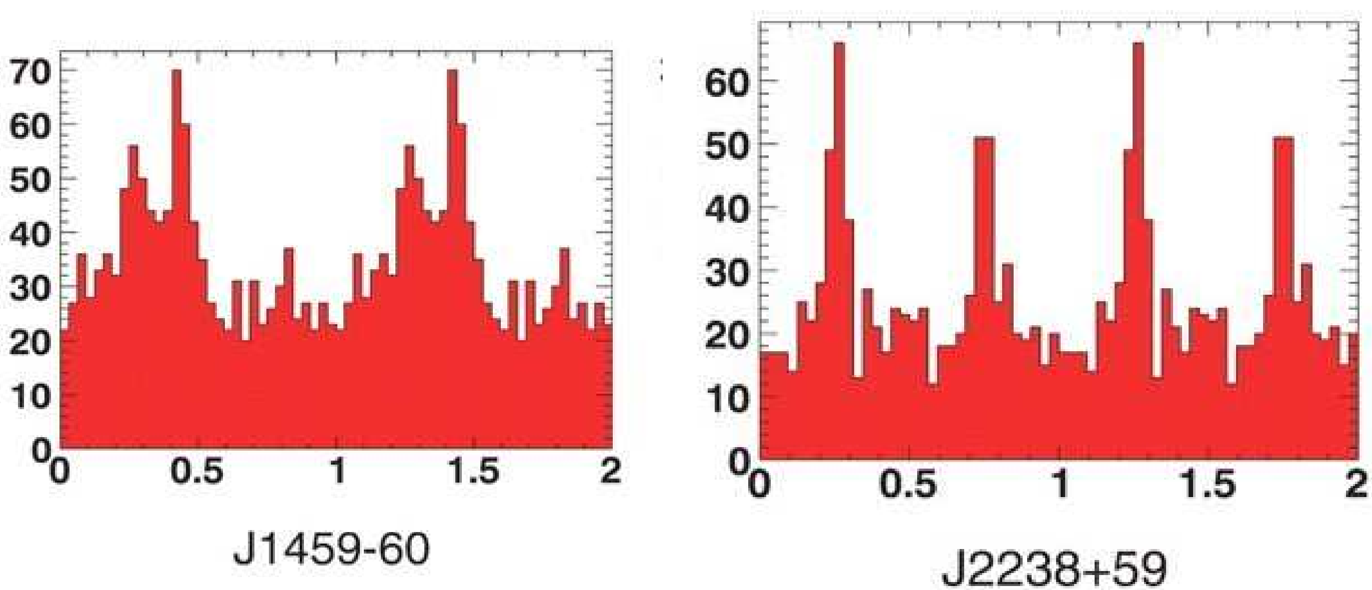

Figure 1: Two examples of the Fermi LAT phase-folded lightcurves *Left panel*: J1459-60 *Right panel*: J2238+59, From Abdo et al. 2009b

References

[1] Abdo, A., Ackermann, M., Ajello, M. & et al., 2009a, Science, submitted
[2] Abdo, A., Ackermann, M., Ajello, M. & et al., 2009b, Science, 325, 840
[3] Abdo, A., Ackermann, M., Ajello, M. & et al., 2009c, Science, 325, 845
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[5] Neutron stars and pulsars, Astrophysics and Space Science Library, 357, 2009, Ed.W. Becker
[6] Cheng, K. S., Ho, C., Ruderman, M. 1986, ApJ, 300, 500
[7] Daugherty, J. K., Harding, A. K. 1996, A&AS, 120, 107
[8] Hobbs, G., Manchester, R., Teoh, A., Hobbs, M. 2004, Young Neutron Stars and Their Environments, Eds. F. Camilo and B. M. Gaensler

B) Immediate Objective:

We will observe six pulsars detected by the Fermi LAT and never previously observed in X-rays (with exception of one pulsar explained above). This is to identify the X-ray counterpart and identify the nature of the spectral and timing emission to increase the number of pulsars for which X-ray, gamma-ray and radio observations exist. These information will allow us to constrain the origin of the high energy emission.

3. Justification of requested observing time, feasibility and visibility

Given below are the targets that we propose to observe in descending order of importance, we place those sources most likely to be detected first. None of these sources have previous detections in X-rays (with the exception of J1614-2230 and J1459-60) so we have had to estimate a minimum count rate. The minimum count rate has been estimated (with the exception of J1614-2230, detailed below) using the photon index from the fitting of the gamma-ray data and the flux from the gamma-ray observation along with the estimation of the interstellar absorption (n_H) in the region of the pulsar using the HEAsoft Galactic H I Column Density inserted into the WebPIMMS (powered by PIMMS v3.9j) and calculated for the pn camera using the medium filter for the total PATTERN=0 count rate. This is the minimum count rate as there maybe supplementary thermal emission in the X-ray domain or a break in the spectrum, not detected in the gamma-ray domain. This is indeed true for the pulsar J1614-2230 which has previously been observed in X-rays with XMM-Newton. Fitting the data reveals a spectrum with a photon index of 2.0, as opposed to the 1.34 determined from the gamma ray emission and the flux is considerably higher, revealing a count rate using WebPIMMS (powered by PIMMS v3.9j) and calculated for the pn camera using the medium filter for the total PATTERN=0 count rate of 0.4 count s^{-1} as opposed to the 0.00046 count s^{-1} determined from extrapolating from the Fermi data.

Pulsar name	est. min. count rate (s^{-1})	requested obs. (ks)	vis. in no. rev. no. revs.	av. visibility (s)	X-ray/radio counterpart	period (ms)
J1614-2230	0.4*	20	37	111214	X-ray/radio	3.2
J1459-60	0.024*	30	52	124298	X-ray	103
J1028-5819	0.0026	50	79	129150	radio	91.4
J0248+6021	0.00002	50	53	116824	radio	217
J1838-0453	????	50	39	104767	radio	380.8
J2238+59	0.000004	50	79	129250	-	163

* = rate derived from X-ray observations

When the minimum estimated count rate is too low, we have requested 50 ks. It is very likely that the change in spectrum between the gamma rays and the soft X-rays will mean that a detection is possible with a significant number of counts, as demonstrated in the case of J1614-2230. We require 20 counts to make a secure detection of the source (from past experience) and > 200 counts to estimate the spectral shape and determine the pulse profile (from past experience).

The XMM-Newton full-frame EPIC observations will allow us to detect any possible X-ray counterparts in the gamma-ray pulsar error error circle for the pulsar with no radio or X-ray counterpart and through spectral and timing analyses we will identify the pulsar in order to improve the position and to gain both spectral and phase folded lightcurve information. Four other pulsars have radio/X-ray counterparts and therefore their position is well known. We will observe these pulsars in small window mode so that a high resolution phase folded lightcurve can be derived to determine the pulse profile and we will use this data to determine a spectrum. The last pulsar is a millisecond pulsar that has previously been observed using XMM-Newton, but in the full frame mode. Because of the short period (P = 3.2 ms) the pulse profile can not be determined using the full frame data (which has a time resolution of 73.4 ms). We will observe this using the pn timing mode.

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 six false colour images of globular clusters to the XMM-Newton Image Gallery.

5. Most relevant applicant's publications

(related to the subject of this proposal and especially publications resulting from accepted XMM-Newton proposals during the past two years)

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*

Rea, N., et al. 2009, MNRAS, 396, 2419: *The first outburst of the new magnetar candidate SGR 0501+4516*

Rea, N., et al. 2008, ApJ 686, 1245: *Resonant cyclotron scattering in magnetars' emission*

Rea, N., et al. 2007, MNRAS, 381, 293: *Very deep X-ray observations of the AXP 4U 0142+614*

Rea N., et al. 2005, MNRAS 361, 710: *Post-glitch Variability in the Anomalous X-ray Pulsar 1RXS J170849.0-400910*

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*

Abdo, A. A., Ackermann, M., Ajello, M., et al., 2009, Science, 325, 845: *Detection of High-Energy Gamma-Ray Emission from the Globular Cluster 47 Tucanae with Fermi*

Abdo, A. A., Ackermann, M., Ajello, M., et al., 2009, Science, 325, 840, : *Detection of 16 Gamma-Ray Pulsars Through Blind Frequency Searches Using the Fermi LAT*