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# Search for binary milli-second pulsars in unidentified Fermi sources

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**Abstract.** We report on the preliminary results of a pilot project of multi-wavelength observations of candidate milli-second pulsars associated with unidentified $\gamma$-ray sources detected by *Fermi*, carried out with both ground and space-based observatories, and on the possible identification of three new binary milli-second pulsars.

**Key words.** Stars: pulsars – Stars: binaries – Gamma rays: stars

## 1. Introduction

The *Fermi* Gamma-ray Space Telescope, launched in June 2008, has marked a revolution in our knowledge of the $\gamma$-ray sky, thanks to the unprecedented performances of its Large Area Telescope (LAT; Atwood et al. 2009). The Third *Fermi*-LAT Gamma-ray Source Catalogue (3FGL; Acero et al. 2015), based on its first four years of operations, contains 3033 sources. This is a factor of ten more $\gamma$-ray sources than known before the launch of *Fermi*. Interestingly, only 238 $\gamma$-ray sources have been firmly identified, e.g. through a characteristics timing signature, such as pulsations, in the case of $\gamma$-ray pulsars, or long term variability for Active Galactic Nuclei (AGN). Another 1785 $\gamma$-ray sources have been *associated* with objects in master catalogues based upon positional coincidence but have not yet been identified, though. The remaining 1010 sources have not even a tentative association. Among the identified $\gamma$-ray sources, pulsars are the most numerous class, with 205 of them identified to date[1]. Of these, 144 are radio loud, i.e. they are detected as radio pulsars, whereas 61 are radio quiet, i.e. no radio pulsations have been detected in spite of deep searches. Surprisingly, nearly half of the $\gamma$-ray pulsars are milli-second pulsars (MSPs), old ($\gtrsim$ 1 Gyr), less energetic ($\dot{E}_{\rm rot} \sim 10^{33}$ erg s$^{-1}$) and low-magnetised ($B \sim 10^8$–$10^9$ G) pulsars, whose rotation has been spun-up by accretion of matter from a companion star. Out of the 93 $\gamma$-ray MSPs, 73 are indeed in binary systems with white dwarf (WD) or low mass main sequence (MS) companions. Of particular interest are a

[1] `https://confluence.slac.stanford.edu/display/GLAMCOG`

class of MSPs with tight orbital periods ($P_{\rm orb}$ < 1 d): the Black Widows (BWs), with companion masses $M_{\rm com} < 0.1 M_\odot$, and the Redbacks (RBs), with $M_{\rm com} \sim 0.1$–$0.4 M_\odot$. They owe their nicknames to species of female spiders that use to devour their male companions after mating, either completely (BWs) or partially (RBs). Indeed, it is through that in these systems the low masses of the companions are the result of their ablation caused by irradiation from the pulsar wind, which ultimately forms an isolated MSP. Before *Fermi*, only a handful of such systems were known in the Galactic field. Now, this number has increased by a factor of five. One peculiarity of BWs and RBs is their elusiveness in radio, owing to radio eclipses and radio pulses delays caused by the intra-binary plasma from the irradiated companion star surface. Indeed, some BWs have been identified from the optical modulation of the companion flux prior to the detection of radio/$\gamma$-ray pulsations (see Salvetti et al. 2015 and references therein). Many unidentified $\gamma$-ray sources at high Galactic latitude might be either BWs or RBs that escaped radio detection so far, but that can be pinpointed in multi-wavelength observations. Therefore, in 2014 we started a pilot project to search for BWs/RBs in unidentified *Fermi* sources based on the detection of optical modulations from the putative MSP companions.

## 2. MSP candidates follow-ups

As a first step, we selected a sample of MSP candidates from the unassociated *Fermi*-LAT sources in the 2FGL catalogue (Nolan et al. 2012), which was the reference catalogue available back then. The selection was based on their $\gamma$-ray spectral and temporal characteristics and was implemented through an artificial neural network code (Salvetti 2016). We further selected potential targets among $\gamma$-ray sources with adequate X-ray coverage, either from *XMM-Newton* or *Swift*, since MSPs are also X-ray sources, with the X-ray emission produced from the pulsar magnetosphere (or hot polar caps on the pulsar surface) and/or from the intra-binary shock (Roberts 2013). Finally, we selected those targets for which multi-epoch photometry measurements were available from public sky surveys. In particular, ten sources in our sample were observed as part of the Catalina Sky Surveys (CSSs) (Drake et al. 2009). Out of them, we could recover the optical periodicity in the MSP candidates 2FGL J0523.3−2350 (Strader et al. 2014) and 2FGL J1653.6−0159 (Romani et al. 2014), both found using the same CSS data. For the other eight MSP candidates, there were cases where no X-ray source was detected within the LAT error box, or X-ray sources were detected but with no CSS counterpart, or with a non-variable CSS counterpart. Two of our MSP candidates have been actually found to be isolated MSPs and another (2FGL J1630.3+3732) to be a binary MSP ($P_s$ = 3.32 ms), PSR J1630+3734.

We carried out dedicated follow-up observations of seven MSP candidates with the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND; Greiner et al. 2008) at the MPI/ESO 2.2m telescope on La Silla (Chile). We carried out simultaneous observations in the optical $g, r, i, z$ and near-infrared $J, H, K$ bands repeated with a regular cadence on two or more consecutive nights. All our targets have ad adequate X-ray coverage of the LAT error boxes with either *XMM-Newton* or *Swift*. The observations were distributed in two runs, in August 2014 and February 2015. The data were processed and calibrated using the GROND pipeline, which also carry out a variability analysis. One of the most interesting targets of our sample is 2FGL J2039.8−5620 ≡ 3FGL J2039.6−5618, a relatively bright $\gamma$-ray source, with a $\gamma$-ray flux $F_\gamma = (1.71 \pm 0.14) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (Acero et al. 2015) and a photon index $\Gamma_\gamma = 1.96 \pm 0.08$. We observed the source in 2013 with *XMM-Newton* (PI: Mignani) for a total exposure time of 44.6 ks. The brightest X-ray source within the LAT error box has a spectrum well described by a power-law (PL) with photon index $\Gamma_X = 1.36 \pm 0.09$, as observed in several BW/RB sources, hydrogen column density $N_H < 4 \times 10^{20}$ cm$^{-2}$, corresponding to an unabsorbed 0.3–10 keV X-ray flux $F_X = 1.02 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (Salvetti et al. 2015). More interestingly, the X-ray source feature a

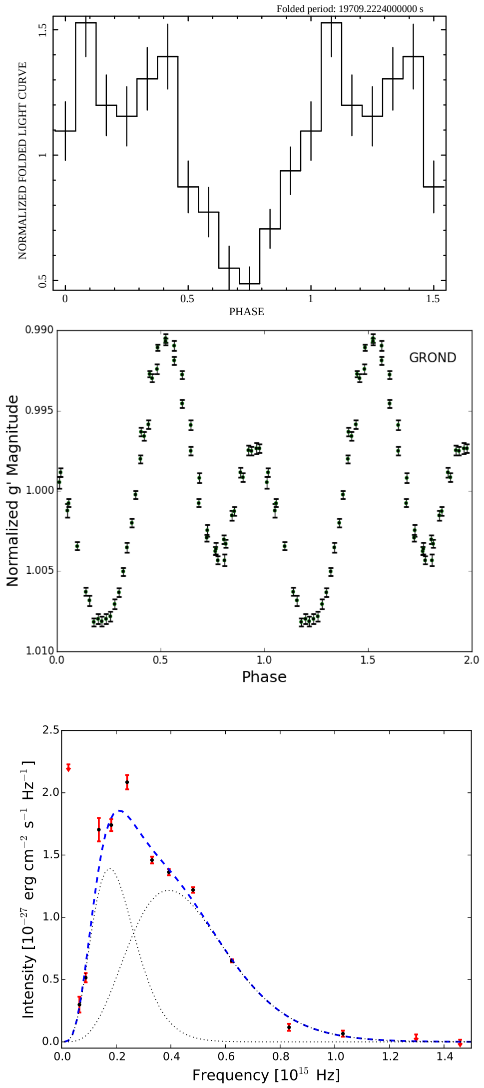


**Fig. 1.** Top to bottom: *XMM-Newton* light curve of the 3FGL J2039.6−5618 counterpart. GROND light curve and spectrum of its optical counterpart from GROND, UVOT, OM, and *WISE* data. The X-ray and optical light curve are aligned in phase. The dotted lines are the two BB components.

modulation with a period of 0.2245±0.0081 d, with a double-peaked light curve (Fig.1, top). We tentatively attributed this modulation to the orbital period of a binary system in a tight orbit. The same periodicity, although more accurate (0.22748±0.00043d), we found in the optical counterpart to the X-ray source detected by GROND (Fig.1, middle), with a double peaked light curve profile. On one hand, this confirmed the association of the X-ray source with its optical counterpart on the other, confirmed the binary system scenario. The asymmetry in the peak intensities is consistent with what observed in known RB systems. The optical counterpart of the X-ray source has been also detected in the CSSs (217 epochs) but the error bars attached to the single flux measurements do not allow to confirm the periodicity observed in the GROND data. This has been confirmed by an independent re-analysis of our GROND data by Romani (2015), who complemented them with data taken with the SOAR and Dark Energy Survey (DES) telescopes, allowing one to extend the time baseline for the light curve folding and improve on the period accuracy determination. By fitting the GROND light curve profile with a simple geometrical model of a tidally distorted companion star (Salvetti et al. 2015) we could determine the orbit inclination (48.9±0.6 degrees) and the epoch of quadrature (MJD=56884.9667±0.0003). We used the GROND data to characterise the phase-averaged spectrum together with optical/ultraviolet data from the *XMM-Newton* Optical Monitor (OM) and the *Swift* Ultraviolet Optical Telescope (UVOT), to which we now added mid-infrared data from the *Wide-Field Infrared Survey Explorer* (*WISE*). The data (Fig.1, bottom) indicate a composite spectrum, with two blackbodies (BBs) with $T_{\rm eff}\sim$3700 K, dominating in the optical/ultraviolet, and $T_{\rm eff}\sim$1700 K, dominating in the near/mid-infrared, respectively, consistent with the new *WISE* fluxes. No clear evidence of spectral variations emerges from the analysis of the multi-epoch GROND data. The origin of the near/mid-infrared emission is unclear. Since modulations are seen in the JHK GROND light curves, the emission from the companion star, likely associated with the hotter BB component, must contribute in the near-IR. The colder BB, however, cannot be associated with emission from the star. More likely, it is associated with emission from cold intra/extra-binary ma-

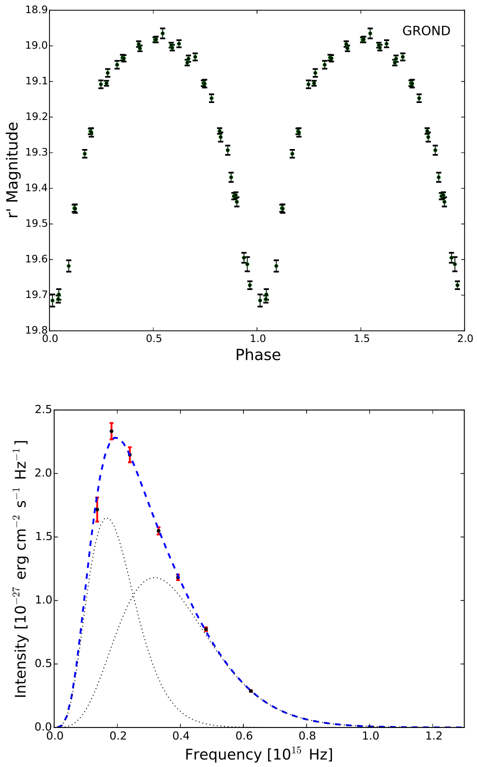


**Fig. 2.** Top to bottom: GROND light curve and spectrum of the 3FGL J0744.1−2523 candidate counterpart. The two BBs are shown as dotted lines.

terial, perhaps associated with the ablated gas from the companion or a residual of an accretion disk, or both. Interestingly, the size of the emission region is a few times that of the star Roche Lobe, which would corroborate the former hypothesis. We did not found evidence of variability in the multi-epoch *WISE* data, as it would be expected if the mid-IR emission comes from diffuse gas. About the other MPS candidates in our sample, we found a candidate X-ray counterpart to 2FGL J1120.0−2204, associated with a GROND source tentatively variable with a period of ∼ 0.33 d. For 2FGL J1036.1−6722, J1539.2−3325, J1625.2−0020 there was no candidate X-ray counterpart associated with a possibly variable GROND source. For 2FGL J0744.1−2523 ≡ 3FGL J0744.1−2523 we found a clearly modulated GROND source within the 3FGL error ellipse, with a period of ∼ 0.115 d (Fig.2, top). The source is a candidate companion of an MSP in a tight binary system. However, no associated X-ray source has been detected in 23 ks *Swift* observations down to a 0.3–10 keV flux limit $F_X = 3.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. Therefore, we cannot firmly rule out that the GROND source is associated with a binary with two classical stars (W UMa or Lyr types) or with a cataclysmic variable (CV), although an orbital period of ∼ 0.115 d would exclude such systems. Interestingly, its spectrum (Fig.2, bottom) is very similar to that of the optical counterpart to 3FGL J2039.6−5618 (Fig. 1, bottom), with cold and hot BBs at comparable temperatures, possibly suggesting a similar nature.

## 3. Conclusions

Our results show that our classification method works pretty well in selecting MSP candidates, with many of our targets turning out to be actual MSPs. The search for binary MSPs through detection of optical modulations has proven to be a successful strategy. Through our pilot project we found two binary MSP candidates (3FGL J2039.6−5618 and 3FGL J0744.1−2523) and one more to be explored (2FGL J1120.0−2204). $\gamma$-ray periodicity searches are in progress for both 3FGL J2039.6−5618 and 3FGL J0744.1−2523, although for the latter are more difficult owing to the more uncertain period. We are carrying out multi-wavelength follow-ups of these sources, including the search for radio pulsations, and are completing the X-ray/optical coverage of the best MSP candidates.

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