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γ-RAY PULSARS IN THE GALACTIC BULGE: A MULTIWAVELENGTH QUEST

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Abstract. A vast majority of γ-ray pulsars were detected by the Fermi-LAT, in the Galactic disk and in globular clusters, but no discovery was ever made in the Galactic bulge. However, strong hints indicate that the latter hosts a population of millisecond pulsars (MSPs). One of them is the existence of an extended γ-ray emission detected by the Fermi-LAT, the Fermi GeV excess, interpreted as the cumulative emission of MSPs too faint to be detected individually. We recently developed a multi-wavelength method to search for bulge MSPs and first demonstrated that about a hundred MSPs, unresolved by the Fermi-LAT and contributing to the GeV excess, should already have been detected by the Chandra X-ray observatory. These progresses allowed us to select promising MSP candidates among X-ray sources with no or very faint ultraviolet, optical and infrared counterparts, while considering a radio counterpart as a strong hint in favor of a pulsar nature. Some candidates were identified as compact objects, possibly being magnetic cataclysmic variables, quiescent low-mass X-ray binaries or, of course, pulsars. We are now collecting novel radio data towards our candidates and investigating the challenging pulsation detection.

Keywords: Fermi, excess, millisecond pulsars, compact object, multi-wavelength

1 Introduction

Pulsars are fast-rotating and highly-magnetized neutron stars. They are formed from violent supernovae explosions and their core density exceeds the nuclear density. Therefore, they are undeniably part of the most extreme astrophysical objects. Their beamed emission originating from the magnetic poles is detected as regular pulses when the beam sweeps the Earth. This is only possible if the magnetic and the rotation axes are not identical, producing a lighthouse effect. The fastest pulsars are called millisecond pulsars (MSPs) and are generally defined by a period smaller than 30 ms. They are sometimes referred to as *recycled* pulsars because they are thought to have been spun up in a binary system by the accretion of matter from their companion (Bhattacharya & van den Heuvel (1991)). Hence, MSPs are older than normal pulsars, sometimes called *young* pulsars. The Galactic bulge is a great place to look for old stars and binary systems and therefore, for MSPs. Moreover, a mysterious γ-ray signal was detected by the Fermi-LAT (Ajello et al. (2016)), peaking at the Galactic center, with a spectrum compatible with a cumulative emission of MSPs. These hints support the idea of a population of bulge MSPs, however MSPs were only detected in the Galactic disk and in globular clusters so far.

Bulge MSPs are hiding. Their detection is challenging but can benefit from the use of a multi-wavelength approach. In Berteaud et al. (2021), we simulated the bulge MSP population, assuming that it causes the entire GeV excess, *i.e.* with the same γ-ray luminosity and the same morphology. We derived an empirical relation between the γ- and X-ray emission of known MSPs in order to provide an X-ray emission to the simulated pulsars. Comparing this emission to the sensitivity of past Chandra observations, we found that about a hundred MSPs could have been detected by the X-ray observatory in a region of $6^\circ \times 6^\circ$ around the Galactic center. In Section 2, we describe how, starting from our simulation and using various catalog of sources, we selected MSP candidates. Section 3 focuses on the most promising candidates for which we started follow-up studies. Finally, Section 4 reviews how the astrophysics community can further probe the bulge MSP population.

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2 Multi-wavelength selection of millisecond pulsar candidates

2.1 X-ray

The results found in Berteaud et al. (2021) incite to look for MSP candidates among the unidentified sources of the Chandra Source Catalog 2.0 (Chen et al. (2019), hereafter CSC). We found about 7000 non-extended and non-variable sources in our region of interest. Using this sample, we made a conservative selection essentially based on the available spectral shape and gave the benefit of the doubt to sources with too few or no spectral information. Relevant quantities such as flux ratios and band fractions were computed for CSC sources on the one hand and for the simulated MSPs on the other hand. Comparison between the two sets of quantities enabled a selection of CSC sources with spectral properties compatible with the ones expected for detectable bulge MSPs. About 3500 candidates, *i.e.* half of the initial selection, were rejected in this first loose but fundamental selection.

2.2 Ultraviolet and optical

The ultraviolet (UV) and optical emission of MSPs is not expected to be strong. Our simulation showed that the X-ray detectable bulge MSPs should lie at galacto-centric distance *i.e.* 8.5 kpc for the large majority, and 5.2 kpc away from us for the closest ones. In those regions, the hydrogen column density easily reaches 10^{22} cm^{-2} and therefore, the absorption of mildly-energetic photons is considerable. Plus, as flux decreases with the distance squared, most of the bulge MSP UV and optical emission can never be detected on Earth. We cross-matched the position of our X-ray selected MSP candidates with the XMM-OM (Page et al. (2012)) and Gaia DR3 (Bailer-Jones et al. (2021)) catalogs according to their angular separation. Any UV or optical source found closer than the major radius of the 95% error ellipse of the Chandra source discarded the latter from our selection. Our goal here was not to be conservative anymore, but rather to focus on the candidates presenting no possible UV and optical counterpart. About 2000 such candidates were found.

2.3 Infrared

The infrared (IR) emission of MSPs suffers from the same disadvantages as the UV and optical emission, *i.e.* it is expected to be very faint, but in this case a quantitative criterion defines *very faint.* Lin et al. (2012) showed that in most cases, compact objects including pulsars verify $\log_{10}(F_X/F_{\mathrm{IR}}) > 0.5$ where F_X is the X-ray flux detected by XMM and F_{IR} the K-band infrared flux. The XMM and Chandra energy bands are slightly different, therefore we adapted this equation for Chandra fluxes. Following the previous procedure, we looked for IR counterparts among the 2MASS (Cutri et al. (2003)), Glimpse (Spitzer Science (2009)) and VVV (Minniti et al. (2017)) catalogs. About 1400 objects survived this new selection, including about 40 sources identified as compact objects, the other having no IR counterpart.

3 Most promising candidates

3.1 Compact objects

As shown in Section 2.3, our selection includes some compact objects presenting only a strong X-ray emission and a faint IR emission. In that respect, they represent some of our most promising MSP candidates but we cannot ignore that some other types of compact X-ray sources such as low mass X-ray binaries in quiescence (qLMXB) and cataclysmic variables (CVs) could pollute our selection. We selected two of our compact objects for a Chandra proposal, in which we demonstrated that 15 ks of additional observations are necessary to differentiate between the Bremsstrahlung continuum from CVs and the hard power-law spectrum of MSPs, unfortunately very similar to the low-temperature black-body spectrum of qLMXBs. Nonetheless, both types of sources are interesting objects to study and rejecting the CV nature is in any case a progress. Computing the cumulative spectrum of our compact objects could also reveal the presence (or absence!) of the very characteristic iron emission lines of CVs.

3.2 Radio sources

We also found radio counterparts to some of our candidates in unpublished VLA imaging data. The fact that only this emission and the X-ray one is detected points towards a pulsar nature. Sobey et al. (2022) selected pulsar candidates among newly detected polarized radio sources with no optical, IR and γ-ray counterparts and successfully discovered two nearby (closer than 1.6 kpc) pulsars thanks to timing observations.

As our radio candidates were detected by Chandra, they must lie between 5.2 and 8.5 kpc away from us (see Section 2.2) which implies that their electron column density DM *i.e.* the electron density integrated along their line of sight is high, from 300 to 1300 pc/cm^3. Therefore, the scattering of radio pulses complicates the detection. The larger it is, the weaker and broader the pulses will be, that is why deep targeted radio observations are needed to identify bulge MSPs.

To motivate this kind of observation, we computed the minimal detectable period as a function of the observing time and the observation frequency using the radiometer equation. An example of the results we got is shown in Figure 1. We wrote several proposals for various radio telescopes (Nançay Radio Telescope, Parkes, Green Bank Telescope) and obtained about 60 hours of observation dedicated to the search of pulsations coming from our MSP candidates. Our observations will reveal any pulsation period larger than 1 ms for the best candidates (the fastest pulsar known to date has a period of ∼1.4 ms) and rule out the young pulsar nature (P $\geq$ 30 ms) for candidates with the highest DMs.

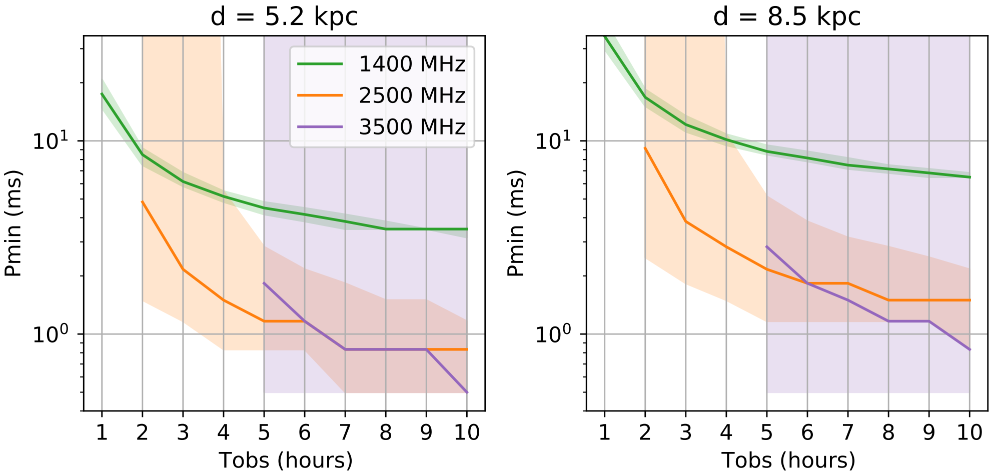

Fig. 1. Minimal detectable period $P_{\min}$ of a promising MSP candidate as a function of the observing time T_{obs} for three different frequencies and two different distances (*i.e.* DM). The radio flux of the source, needed for the computation, was extrapolated from the VLA L-band (∼1.5 GHz) one, assuming a power-law spectrum ($S_\nu \propto \nu^{-\alpha}$ with $\alpha = 1.59 \pm 0.73$ where ν is the frequency). These plots show the results for an observation with the Parkes telescope. At 2.5 GHz and for long observations, the uncertainty due to the flux extrapolation (represented by the shaded area) is reasonable and short periods can be detected.

4 Future prospects: how will the community help

In Section 3, we explained how we motivated observations of promising MSP candidates in X-rays and in radio with existing telescopes, but future instruments also have the potential to reveal the hidden bulge MSPs, and turn our multi-wavelength quest into a *multi-messenger* quest:

- In Section 3.2, we showed that deep targeted radio observations are needed for the identification of bulge MSPs. This results was foreseen by Calore et al. (2016) who not only demonstrated that current radio surveys are not sensitive to the bulge MSP population responsible for the GeV excess, but also that, on the contrary, future surveys with MeerKAT and SKA could detect up to a hundred of bulge MSPs.

- The number of MSPs needed to reproduce the GeV excess, and therefore in our simulation, is of the order 10^4. Such a large number of fast-rotating sources should produce a gravitational wave signal, and Calore et al. (2019) demonstrated that the latter will be detectable within one year of third generation detectors such as Cosmic Explorer and Einstein Telescope.

- Finally, Macias et al. (2021) recently showed that CTA could detect the inverse Compton scattering signal caused by the bulge MSP population. The latter is expected to inject an important quantity of high-energy electrons and positrons able to up-scatter ambient photons to TeV energies and therefore detectable by CTA.

5 Conclusion

The presence of a population of MSPs in the Galactic bulge is supported by evidence, including the Fermi-GeV excess. The Fermi-LAT is not sensitive enough to detect these pulsars as individual point sources and neither can current radio surveys unveil their pulsed emission. Deep radio timing observations are the most favorable way of identifying MSPs in the Galactic bulge, but require wisely chosen target sources. Starting from X-ray data, we conservatively selected MSP candidates and gradually reduced this selection to the most promising ones by investigating their multi-wavelength counterparts. Our best candidates are either identified as compact objects, *i.e.* with a strong X-ray emission and a faint IR emission only, or detected in X-ray and radio exclusively. For both types, we proposed further X-ray or radio observations that will help us understand the nature of these intriguing sources. The multi-messenger community will also help solving the Fermi GeV excess mystery thanks to future radio surveys, third generation gravitational wave detectors and Cherenkov telescopes.

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