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IDENTIFICATION OF COMPACT OBJECTS AT THE GALACTIC CENTER

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Abstract. Unresolved point sources, namely millisecond pulsars (MSPs), are thought to contribute to an enigmatic signal detected in γ rays: the Galactic Center Excess. The detection of these sources at longer wavelengths will shed light on this long-standing puzzle, also related to dark matter. We present our recent progress in our search for MSPs among yet unidentified X-ray sources: 1. Infrared data helped us to identify compact objects among a large sample of promising X-ray MSP candidates; 2. A dedicated X-ray spectral analysis revealed contamination of our initial sample by a population of cataclysmic variables; 3. Finally, we are also conducting radio observations aiming at detecting millisecond pulsations.

Keywords: pulsar, compact objects, multi-wavelength, Galactic center

1 Introduction

The γ-ray sky has been observed by the *Fermi* Large Area Telescope (LAT) for almost 15 years. It shows a bright emission towards the Galactic plane and numerous point sources all across the sky that can be masked in order to study the diffuse emission alone. The latter is a linear combination of emissions from π^0 decay, Bremsstrahlung (both spatially correlated with the interstellar medium), inverse Compton scattering (with the interstellar radiation field), the huge *Fermi* bubbles and an extragalactic isotropic emission. However, towards the Galactic center, this standard model of diffuse γ-ray emission does not correctly reproduce the *Fermi* data without accounting for a signal of mysterious origin, dubbed the Galactic Center Excess (GCE). Goodenough & Hooper (2009) discovered this signal less than one year after the launch of the LAT and claimed to have found a possible sign of dark matter annihilation into γ rays toward the Galactic center, by analyzing the spectral shape and the spatial distribution of the photons detected by the LAT. Two years later, Abazajian (2011) showed that the spectrum of the GCE was also compatible with the one of globular clusters, known to host a large population of millisecond pulsars (MSPs), suggesting that these highly magnetized and fast rotating neutron stars could be the origin of the excess. Further studies suggested that the emission was extended (Calore et al. 2015; Daylan et al. 2016), coming from the bulge (Bartels et al. 2018a; Macias et al. 2018) and at least partly from point sources (Calore et al. 2021; List et al. 2021). Not only would the discovery of MSPs towards the Galactic center improve our understanding of the GCE and its relation to dark matter, but it would also *e.g.* constrain the models of free electron density in the Milky Way and allow astrophysicists to test the gravitational potential of the region. Moreover, with its high density and profusion of massive stars, the Galactic center is the perfect place to look for compact objects (COs).

2 Simulation and X-ray detectability of the Galactic bulge MSP population

In Berteaud et al. (2021), we performed a Monte Carlo simulation* of the Galactic population of MSPs, which we supposed to be made of two components: the disk and the bulge. The former is well constrained from observations and we used the spatial distribution and γ-ray luminosity function (GLF) found by Bartels et al. (2018b) who used the data of ~ 100 MSPs detected by the LAT and accounted for the sensitivity threshold of the telescope. The existence of a population in the bulge is speculative and is the putative origin of the

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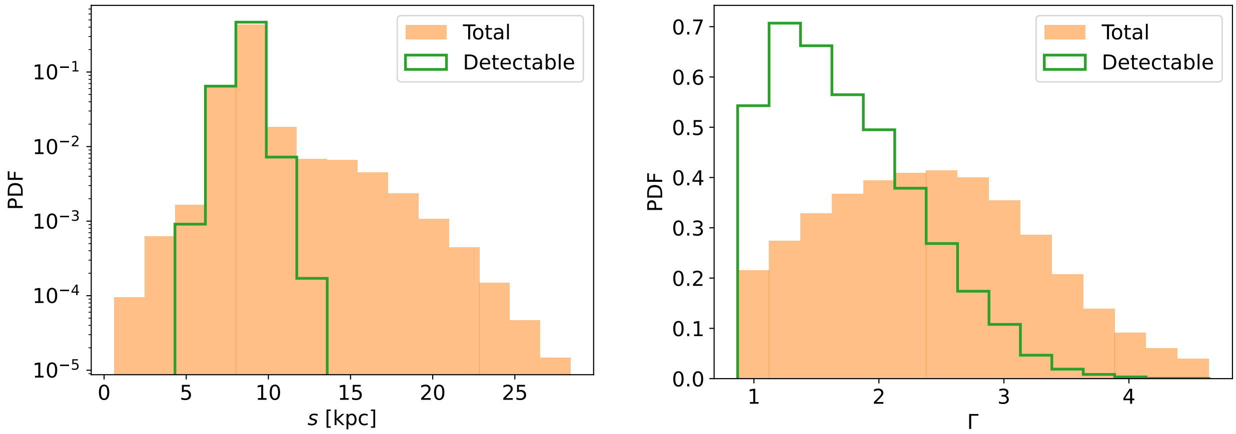

Fig. 1. *Left:* Probability density function (PDF) of the distance s of simulated MSPs in the global population (orange) and in the X-ray detectable one (green). *Right:* Same as left but for the X-ray spectral index Γ.

GCE. We used the spatial distribution of the excess found by Bartels et al. (2018a) and the same GLF as in the disk for our simulation. We constructed a γ-to-X emission model and obtained a population of $\sim$ 14 000 sources in our region of interest (ROI, $|l|, |b| < 3°$) with an absorbed X-ray flux F_X^{abs} between 10^{-22} and 10^{-12} erg/cm^2/s. About a hundred of them, with a negligible contribution from the disk, have F_X^{abs} larger than the detection threshold the *Chandra* X-ray observatory, meaning that this telescope could have detected some bulge MSPs in past observations. According to our simulation, these sources would be located at 5.2/11.9/8.5 kpc at minimum/maximum/on average and would be rather hard compared to the global population, as can be seen in figure 1.

3 Millisecond pulsars candidates

3.1 Multi-wavelength selections

In Berteaud et al. (2021), we also selected MSP candidates in the *Chandra* Source Catalog. Among non-variable, non-extended objects with a rather hard emission, we excluded those with a *Gaia* counterpart either too close (< 5.2 kpc) or too far (> 11.9 kpc) from us. The association between *Chandra* and *Gaia* sources is not known *a priori* and we performed a geometrical cross-match between both catalogs, *i.e.* we considered as counterparts two sources for which the angular separation is less than the error radius of the X-ray source. With this method, we identified more than 3100 MSP candidates in our ROI, *i.e.* more than what was expected from the simulation, demonstrating that the X-ray data do not exclude the MSP origin of the GCE. Therefore, we recently made additional cuts on our selection, following the idea that the optical, ultraviolet (UV) and infrared (IR) light from MSPs should not be bright, and anyways highly absorbed if in the bulge. Again, we performed geometrical cross-matches (accounting for the counterpart error when relevant) and we excluded those sources with optical, UV and strong IR emission, while the ones with faint IR emission were tagged as potential COs, according to the criterion of Lin et al. (2012):

$$\log_{10}(F_X/F_{IR}) > 0.5, \tag{3.1}$$

where F_X and F_{IR} are the unabsorbed X-ray and the IR flux. About 1400 sources survived these selections and more than 50 of them were tagged as CO candidates.

3.2 Cumulative X-ray spectrum

Most of the candidates mentioned above are too faint to perform a dedicated spectral analysis. Therefore, we combined the X-ray spectra of our $\sim$ 1400 sources in order to shed light on the general properties of this population. The cumulative X-ray spectrum of our candidates shows a prominent line between 6 and 7 keV, that we interpreted as an iron K-shell line. This feature is characteristic of cataclysmic variables (CVs), a type

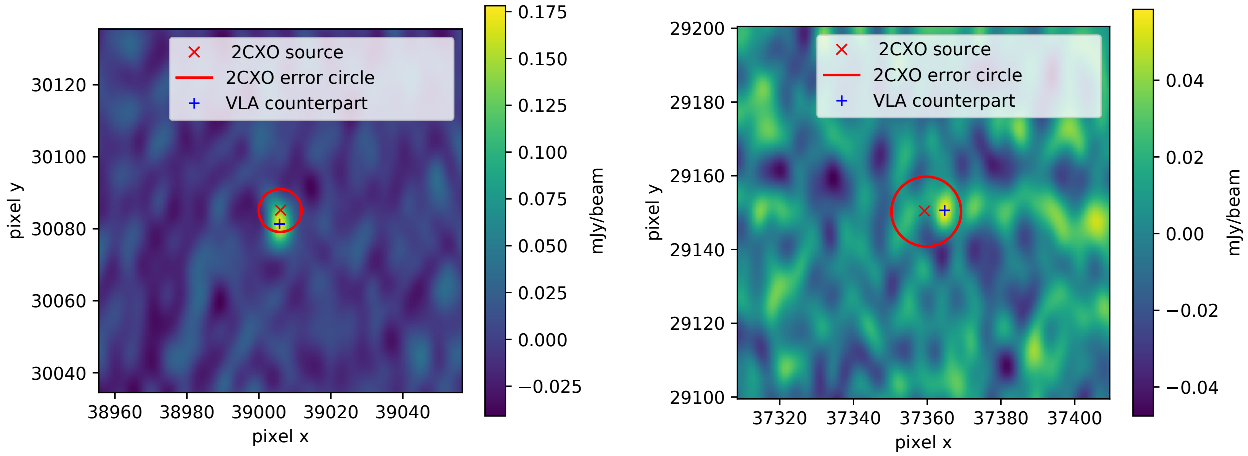

Fig. 2. Identification of the radio counterpart of 2 MSP candidates detected in X-rays in VLA imaging data (colored background). The positions and error circles of the *Chandra* (2CXO) sources are shown by the red crosses and circles. The blue cross indicates the position of VLA sources whose distance from the MSP candidate is less than the radius of the error circle.

of CO, which are probably the dominant sources in our ROI (Hong et al. 2009; Jonker et al. 2011). Given the selections that we made, we expected to have included CVs among our MSP candidates. Further investigations will be necessary to disentangle both kinds of sources. Nonetheless, we also created the cumulative spectrum of the sources tagged as potential CO, which encouragingly did not present the same line feature. Moreover, its spectral shape is compatible with the cumulative spectrum of simulated detectable MSPs.

3.3 *Radio counterparts*

In order to complete the counterpart search that we described in section 3.1, we analyzed unpublished radio imaging data collected from 28h of observations of the Very Large Array (VLA) in the region $|l| < 1°$, $-1° < b < 2°$ (PI: M. Kerr). Unlike optical, UV and IR light, the radio emission of MSPs is especially strong. We used a source detection algorithm, `PyBDSF`[†], in $\sim$ 20-arcsec boxes around the $\sim$ 900 candidates covered by the VLA observations to identify radio sources in the vicinity of our MSP candidates and required the distance between the X-ray and the VLA sources to be less than the *Chandra* error radius in order to consider a match. Each match was then carefully inspected. Some of the sources detected by `PyBDSF` were actually noise, others were spatially extended. For the rest, we made sure, by looking for their position in VizieR, that we did not miss any potential counterparts. With this method, we identified promising MSP candidates: 5 with only X-ray and radio emission, plus one tagged as CO. In figure 2, we show the radio image of two of them. The non-detections of the other candidates cannot rule out their pulsar nature, given the noise level of the VLA image.

4 Radio timing follow-ups

4.1 *Theory*

The radiometer equation is a useful tool to calculate the minimal detectable flux of a pulsar $S_{\rm min}$ as a function of parameters of the radio telescope used for the observation, the duration of the observation $T_{\rm obs}$, the pulsar period P and its observed pulse width $w_{\rm obs}$:

$$S_{\rm min} \propto \sqrt{\frac{w_{\rm obs}}{T_{\rm obs}(P - w_{\rm obs})}}. \tag{4.1}$$

$w_{\rm obs}$ increases with the dispersion measure (DM) of the pulsar, *i.e.* its column density of free electrons. With a flux smaller than $S_{\rm min}$, the pulsations, characteristic of this type of source, would be indistinguishable from

[†]`https://pybdsf.readthedocs.io/en/latest/`

noise. This equation tells us that the hardest pulsation detections are for pulsars with high DMs, with short periods and low fluxes, which is a pretty accurate definition of bulge MSPs. Calore et al. (2015) indeed showed that current radio surveys are not sensitive enough to the population of bulge MSPs. Hence, deep targeted observations are needed. We used the radiometer equation to calculate the minimal detectable period of the 6 promising MSP candidates from section 3.3, knowing their radio flux thanks to `PyBDSF` and their DM was calculated with `PSRDist` Bartels et al. (2018b), assuming either a distance of 5.2 or 8.5 kpc. We used these results to support several radio observational proposals.

4.2 Observations and data analysis

We obtained about 50h of observations with Parkes and the Green Bank Telescope and performed the pulsation search with `PRESTO`[‡]. For bright pulsars, their signal is usually seen at all wavelengths, during the whole observation, and `PRESTO` finds well-defined period and period derivative. The data analysis is ongoing and preliminary results are encouraging.

5 Conclusions

The Galactic center is the perfect place to look for COs. The existence of a population of MSPs in this region is supported by the discovery of an excess of γ rays and their detection would be a major breakthrough in various domains of physics. We have developed a novel method to select MSP candidates in the direction of the Galactic center, starting from *Chandra* observations. We found more than 1400 X-ray sources with neither optical, nor UV, nor strong IR counterparts. A vast majority of them do not have IR counterparts at all, while the rest respect the CO criterion (equation 3.1). The cumulative X-ray emission of all candidates revealed the presence of CVs in our selection, while the population of potential CO does not seem to be polluted by these sources. Finally, 6 of our sources were also detected in radio, making them very promising candidates for follow-up studies. We obtained more than 50h of timing observations for these targets, and we are currently working on the data analysis. Results will be published in a near future.

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[‡]`https://github.com/scottransom/presto`