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MULTI-WAVELENGTH PROBES OF THE FERMI GEV EXCESS

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Abstract. More than a decade after its discovery, the Fermi GeV excess is still an exciting subject of research. Thus far, an unresolved population of millisecond pulsars (MSPs) in the Galactic bulge shining in γ-rays is the favorite explanation to the excess, but other explanations exist. Data from the Fermi-LAT have been thoroughly studied and, in order to discriminate between the different hypotheses, a multi-wavelength approach is now needed. In a recent study, we demonstrated that if the GeV excess is caused by an MSP population, about a hundred of them could be detectable in X-rays in a region of $6^\circ \times 6^\circ$ about the Galactic center. The comparison with X-ray data allowed us to conclude that the MSP hypothesis is not excluded, as we found more than three thousand MSP candidates in a strictly conservative approach. The few hundred candidates, with good X-ray spectral knowledge and no optical counterpart, are promising MSP candidates.

Keywords: X-rays, γ-rays

1 Introduction

The Fermi Large Area Telescope (Fermi-LAT), launched more than a decade ago, has produced the most detailed γ-ray data to date. Its energy range and spatial resolution showed undeniable progress compared to its predecessor, EGRET. One objective of the Fermi-LAT was to investigate the composition of the dark matter (DM), and when an excess of γ rays around 2 GeV was detected in the direction of the Galactic center, the scientific community naturally got really excited. Straight away, this signal was interpreted as a possible sign of DM annihilation. However, after more than ten years of research, scientists now favor a more astrophysical explanation: an unresolved population of millisecond pulsars (MSPs) hiding in the Galactic bulge. These sources of γ-rays, because too faint, would not be resolved as point sources by the Fermi-LAT, but would contribute to the diffuse emission. The spectral shape of the excess, renamed "Fermi GeV excess" or "Galactic center excess", resembles the one of some globular clusters expected to host MSPs and its spatial morphology follows the stellar over-density of the Galactic bulge. The Fermi-LAT γ-ray data have been thoroughly studied in order to understand the Fermi GeV excess, and a multi-wavelength approach is now needed in order to discriminate between the different hypotheses. Therefore, in a recent work (Berteaud et al. (2021)), we studied the detectability of the MSP population in X-rays. With its unique high spatial resolution and low instrumental background, Chandra is an excellent instrument to detect X-ray sources in the 0.1-10 keV energy band, and therefore the perfect instrument to look for the MSP population in X-rays.

In the first section, we present our spatial and spectral modelling of the MSP population and in the second section, we study the detectability of our population by Chandra and compare our results to data.

2 MSP modelling

In order to assess the detectability of the Galactic Center MSP population by the Chandra X-ray space observatory, we started by modelling the MSP population using Monte Carlo simulation methods such as its spatial and γ-ray spectral properties match the ones of the Fermi GeV excess. Although only bulge MSPs are responsible for the excess, we also modelled disk MSP as they could represent an important source of foreground. Then, we used data of both X-ray and γ-ray detected MSPs to compute the X-ray emission of the population.

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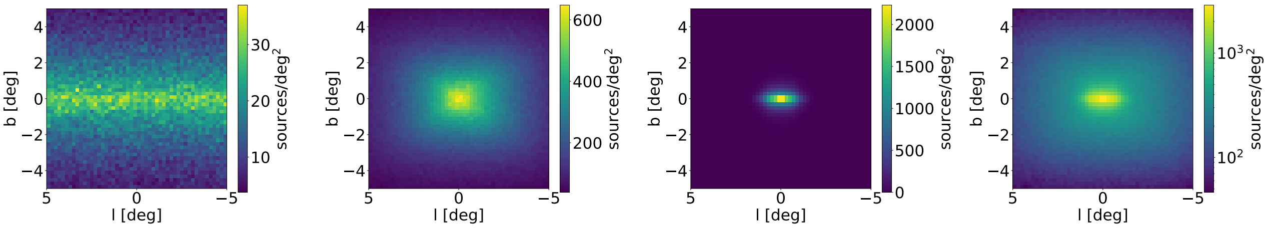

Fig. 1. From left to right, Galactic MSP density in the disk, the boxy bulge, the nuclear bulge and their sum as simulated/modelled by Berteaud et al. (2021).

2.1 *Spatial modelling*

MSPs can be found both in the disk and in the bulge of the Milky Way. Bartels et al. (2018) studied the spatial distribution of disk MSPs and they found the disk MSP number density to be given by a Lorimer disk profile:

$$n(r,z) = \frac{NC^{B+2}}{4\pi R^2 z_s e^C \Gamma(B+2)} \left(\frac{r}{R}\right)^B \times exp\left(-C\left(\frac{r-R}{R}\right)\right) exp\left(-\frac{|z|}{z_s}\right) \tag{2.1}$$

with best-fit parameters B = 3.91, C = 7.54, defining a vertical and radial profile, and $z_s = 0.76$ pc a scale height. The total γ-ray luminosity of the MSP disk population is 1.5×10^{37} erg/s. The bulge is made of a major component, the boxy bulge (BB), described by Cao et al. (2013):

$$n(x_{BB}, y_{BB}, z_{BB}) = K_0\left(\left[\left[\left(\frac{x_{BB}}{x_0}\right)^2 + \left(\frac{y_{BB}}{y_0}\right)^2\right]^2 + \left(\frac{z_{BB}}{z_0}\right)^4\right]^{\frac{1}{4}}\right) \tag{2.2}$$

with $x_0 = 0.69$ kpc, $y_0 = 0.29$ kpc and $z_0 = 0.27$ kpc and K_0 being the modified Bessel function of the second kind. Here, (x_{BB}, y_{BB}, z_{BB}) refer to the Cartesian BB coordinates system. The z_{BB} axis is perpendicular to the Galactic plane and the x_{BB} axis is rotated 29.4° away from the Galactic center-Sun axis in the clockwise direction.

The γ-ray luminosity of MSPs from the boxy bulge adds up to 1.73×10^{37} erg/s. The other parts of the bulge are less bright, with 1.63×10^{36} erg/s for the nuclear stellar disk and 5.89×10^{34} erg/s for the nuclear stellar cluster. Both form the nuclear bulge (NB). Knowing the total γ-ray luminosity of each spatial component and the γ-ray luminosity function allows to deduce the total number of MSPs: 24009 for the disk and 30374 for the bulge . Fig. 1 shows the corresponding Galactic MSP density.

2.2 *Spectral modelling*

Bartels et al. (2018) also studied the γ-ray emission of disk MSPs and found that the best fit MSP γ-ray luminosity (L_γ, 0.1-100 GeV) probability density function can be described by a broken power-law:

$$\frac{dN}{dL_\gamma} \propto \begin{cases} \left(\frac{L_\gamma}{1erg/s}\right)^{-0.97} & L_\gamma \leq 10^{33.24} erg/s \\ \left(\frac{L_\gamma}{1erg/s}\right)^{-2.6} & L_\gamma > 10^{33.24} erg/s \end{cases} \tag{2.3}$$

We made use of this function for both the disk and bulge MSP simulations, although it was constructed from disk data. We have no reason to think the γ-ray luminosity function should be different in the disk and in the bulge. With a γ-ray luminosity and a position for each simulated pulsar, it is possible to calculate a flux. Using γ-ray data from Abdollahi et al. (2020) and X-ray data from Lee et al. (2018), we computed the γ-to-X (unabsorbed) flux ratio F_γ/F_X of 40 MSPs. We noticed a correlation between this quantity and the X-ray spectral index Γ of MSPs and used these 40 data points to fit a 2D probability density function, as can be seen in Fig. 2.

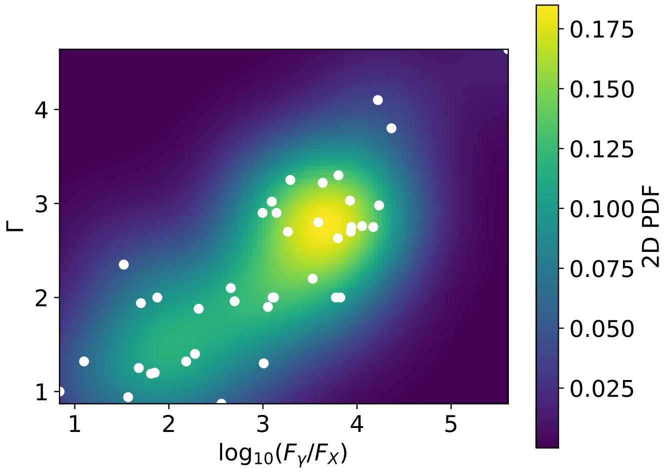

Fig. 2. 2D joint PDF (colored background) of $\log_{10}(F_\gamma/F_X)$ and X-ray spectral index Γ from the 40 MSPs observed in γ-rays and X-rays. Data are shown by the white dots. Figure from Berteaud et al. (2021).

3 Comparison with Chandra data

The current generation of X-ray telescopes is only able to detect the brightest sources, they have a detectability threshold, which means that not all of the 30347 simulated bulge MSPs could be detectable by Chandra. First, we used Chandra sensitivity data to compute the number of detectable MSPs in our simulation. On the other hand, not all Chandra detected sources are MSPs, so we had to make cuts on Chandra data to select only MSP candidates.

3.1 *Detectability of the mock population*

We selected a region of interest (ROI) of $6^\circ \times 6^\circ$ around the Galactic Center and computed the position dependent flux detection threshold of Chandra in this ROI. Then, for each MSP of the synthetic population, we compared its X-ray flux to the flux detection threshold at the source position. If its flux is larger, the MSP is said to be detectable by Chandra. Averaging over 100 Monte Carlo simulations, we found 95 ± 9 detectable MSPs, including 60 from the BB and 34 from the NB. Only one MSP from the disk is detectable on average. These results are illustrated in Fig. 3.

3.2 *Candidate selection*

For a meaningful comparison between the simulation and the data, we select from the Chandra catalog non-variable compact sources whose flux is larger than the flux detection threshold at the source position. With these minimal cuts we selected 6918 sources in our ROI. We reduced this number by excluding sources that cannot be MSP candidates using spectral and distance cuts. These cuts are based on the simulation, only taking into account detectable bulge MSPs as explained below.

Thanks to the X-ray spectral index Γ, we could calculate the X-ray flux of simulated MSPs in different energy bands, and we used these different fluxes to compute various flux ratios. For each of them, we obtained a minimal and a maximal value. Thanks to data collected by Chandra in these same energy bands, we could compute these ratios for the Chandra sources. If for one source, one of the ratios falls outside the minimal and maximal values allowed, this source is not considered as a candidate. If a ratio cannot be computed, the cut is not applied for this ratio.

From our simulation, we learned that detectable bulge MSPs are from 5.24 to 11.98 kpc away from us. These values define our distance cuts. To know the distance between us and the Chandra sources, we cross-matched the Chandra catalog with the Gaia eDR3 distance catalog by Bailer-Jones et al. (2021). If all potential matches of a Chandra source are outside our distance cuts, the source is not considered as a candidate.

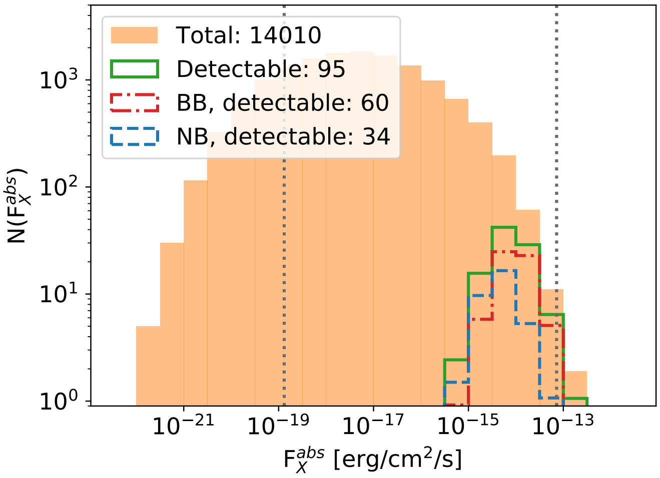

Fig. 3. X-ray energy flux distribution of the synthetic MSP population, averaged over 100 Monte Carlo simulations: Total MSPs in the ROI (orange filled), total detectable MSPs (green solid) including MSPs from BB (red dot-dashed), NB (blue dashed) and disk (not shown). The vertical dotted lines illustrate the validity range of our model extrapolation. Figure from Berteaud et al. (2021).

Applying these cuts allowed to reduce the number of candidates to about 3000, which is more than the hundred of detectable MSPs predicted by the simulation. Therefore the hypothesis is not excluded by the data and such a difference is not surprising knowing that our selection is for sure contaminated by other X-ray sources. From these more than 3000 candidates, we selected the most promising ones as follows: They should have a good spectral knowledge, so all flux ratios should be computable, and should have no Gaia counterpart, regardless of the distance, as optical counterparts of MSPs are known to be very faint. This further reduces the selection to about 300 promising MSP candidates.

4 Conclusion

The nature of the Fermi GeV excess is still to be demonstrated. We showed with Monte Carlo simulations that if it is caused by a population of MSPs, about a hundred of them could be detectable by Chandra in a ROI of $6° \times 6°$ about the Galactic Center. Unlike in γ-rays, the population wouldn't be completely unresolved in X-rays. Therefore, we looked for MSP candidates in Chandra data. Using simulation based cuts, we found more than 3000 candidates in a conservative approach, meaning that the MSP hypothesis as an explanation to the excess is not excluded. Moreover, we also selected about 300 promising sources among these candidates that have a good spectral knowledge and no optical counterpart. Our goal now is to use these candidates for follow-up studies, at radio wavelength for example.

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