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# Dark matter vs. pulsars: Catching the impostor

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**ABSTRACT**
Evidence of excess GeV emission nearly coinciding with the Galactic Centre has been interpreted as a possible signature of annihilating dark matter. In this paper, we argue that it seems too early to discard pulsars as a viable explanation for the observed excess. On the heels of the recently released Second *Fermi* LAT Pulsar Catalogue (2FPC), it is still possible that a population of hard ($\Gamma < 1$) millisecond pulsars (MSPs) either endemic to the innermost region or part of a larger nascent collection of hard MSPs that appears to be emerging in the 2FPC could explain the GeV excess near the Galactic Centre.

**Key words:** (cosmology:) dark matter – gamma-rays: observations – (stars:) pulsars: general

## 1 INTRODUCTION

At first glance, pulsars and dark matter appear to have nothing in common, the former are magnificent spinning neutron stars with impeccable timing (Bell 1968; Gold 1968), while the latter embodies the most profound mystery at the crossroads of gravity and particle physics (Peebles 2013). But, on closer inspection, one actually realises that they share more than meets the eye. Baltz, Taylor & Wai (2007) recognised this seemingly innocuous conflict when they noted that pulsars would be one of the biggest obstacle to proving a dark mater astrophysical signal. An avalanche of recent results has just reinforced the ambiguity (Aharonian et al. 2012; Cholis & Hooper 2013).

This would be purely anecdotal were it not for the fact that we have not identified a dark matter culprit. The underlying reason is that pulsars and dark matter are predicted to share similar spectral signatures with sharp cutoffs, despite dramatically different astrophysical origins. Around pulsars, gamma-ray photons are emitted via curvature radiation of accelerated particles with an exponential cutoff at the maximum curvature energy around a few GeV (Rybicki & Lightman 1979; Abdo et al. 2013). In contrast, a number of dark matter models predict that cosmic dark particles will annihilate into known elementary particles that will subsequently generate secondary photons. The resulting gamma-ray spectrum should show a cutoff near the dark matter particle mass $m_\chi$ (Bergström et al. 2005; Bringmann & Weniger 2012).

This issue has come to bear on current searches for dark matter in the purlieus of the Galactic Centre. The central concentration of dark matter is arguably the most promising place to search for unusual annihilation products. As it turns out, over the past few years a number of groups have noticed the presence of excess GeV emission around the Galactic Centre (Hooper & Linden 2011; Boyarsky, Malyshev & Ruchayskiy 2011; Abazajian & Kaplinghat 2012). Whilst these results are possible breakthroughs in dark matter research, the region over which the excess GeV emission has been found is scientifically daunting with local sources of diffuse emission and unresolved gamma-ray emitters that can easily sequester any secondary emission associated with dark matter.

Procedurally, a final confirmation of dark matter annihilation must exclude all other available astrophysical explanations. Exploiting the spectral shape of the excess GeV emission, Abazajian & Kaplinghat (2012) and Hooper & Linden (2011) have concluded that known gamma-ray pulsars cannot account for such a signal. Most arguments against pulsars have been built around the premise that the spectral shape of *Fermi* pulsars ($0.4 < \Gamma < 2.0$) cannot account for the much harder ($\Gamma \approx 0.5$) spectrum of the GeV excess (Hooper & Linden 2011). These studies lead to the seemingly unavoidable conclusion that we are detecting dark matter annihilation. The true situation is more complicated.

In their favour, the exponential cutoff in pulsars has been measured exquisitely well (Abdo et al. 2013). The observed peak for the excess GeV emission at 1–4 GeV is consistent with the observed cutoff energy for *Fermi* pulsars that tend to cluster around 0.4 GeV $< E_{\rm cutoff} <$ 6 GeV. The average *Fermi* gamma-ray luminosity for MSPs from six months of *Fermi* data also appears to be in the right ballpark of the excess (Wharton et al. 2012). Unlike dark mat-

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ter, the existence of a Galactic Centre population of neutron stars has also been firmly established based on discovery of a handful of pulsars within 15′ of Sgr A$^*$ (Muno et al. 2004a; Deneva, Cordes & Lazio 2009).

Thus, although there are some differences at the astrophysical level, observationally it is still very difficult to tell pulsars and dark matter apart for models with dark matter particle mass $m_\chi$ between 0.1 and 100 GeV. Here we suggest that a population of hard ($\Gamma < 1$) MSPs could still account for the GeV excess at the Galactic Centre. Initially, we estimate the pulsar population needed within a few degrees of the Galactic Centre in the context of the newly released second *Fermi* Large Area Telescope (LAT) pulsar catalogue (Abdo et al. 2013). Next, we motivate and discuss potential reasons for a concentration of hard MSPs in the innermost region. We close with implications and possible ways forward.

## 2 THE GALACTIC CENTRE BY THE NUMBERS

Our first task is to revise the measured pulsar luminosities and certify that it is possible to reproduce the excess GeV emission at the Galactic Centre with the most recent list of *Fermi* MSPs. Using three years of data, the Second *Fermi* LAT Pulsar Catalogue (2FPC) reports a total of 117 gamma-ray pulsars of which 77 are young or middle-aged and 40 are MSPs (Abdo et al. 2013). The updated catalogue nearly triples the previous *Fermi* pulsar list and it appears to be progressively populated by more MSPs with harder photon index $\Gamma < 1$. This is illustrated in Figure 1, where we plot the photon spectral index against the energy flux from 0.1 to 100 GeV for *Fermi* MSPs.

As in Hooper & Linden (2011), we adopt a 0.1 – 100 GeV energy flux of $f_{\rm GC} \approx 8 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ for the GeV excess from the Galactic Centre. At the distance of the Galactic Centre (8.3 kpc), this corresponds to a gamma-ray luminosity $L_{\rm GC} \approx 6.6 \times 10^{36}$ erg s$^{-1}$ $f_\Omega$, where $f_\Omega$ represents the correction factor. Following Wharton et al. (2012), we can estimate the total number of MSPs potentially present in the Galactic Centre from the gamma-ray luminosity $L_{\rm GC}$ and the average luminosity of a typical pulsar $L_\gamma$ using,

$$N_{\rm MSP} = \frac{L_{\rm GC}}{L_\gamma}. \qquad (1)$$

In order to solve this relation, we must first understand the current LAT sensitivity to pulsars. Starting with the predicted sensitivity limits for a pulsar-like spectrum with $\Gamma = 1.8$ and $E_{\rm cutoff} = 2$ GeV reported by Abdo et al. (2013), we have built a sensitivity curve for the entire range of power law indices assuming a pulsar-like exponential cutoff energy spectrum, with a fixed parameter $E_{\rm cutoff} = 2$ GeV

$$G_{100} = \int_{0.1\,\rm GeV}^{100\,\rm GeV} K E^{1-\Gamma} \exp\left(\frac{E}{E_{\rm cutoff}}\right) \, {\rm d}E. \qquad (2)$$

Figure 1 shows the LAT sensitivity from 0.1 to 100 GeV for $b = 0^\circ$ and $|b| = 30^\circ$. Clearly, there is a strong latitude dependence of the sensitivity. In addition, the sensitivity degrades by a factor of $\approx 2$ for harder pulsar spectra. Another source of uncertainty is the diffuse flux in the

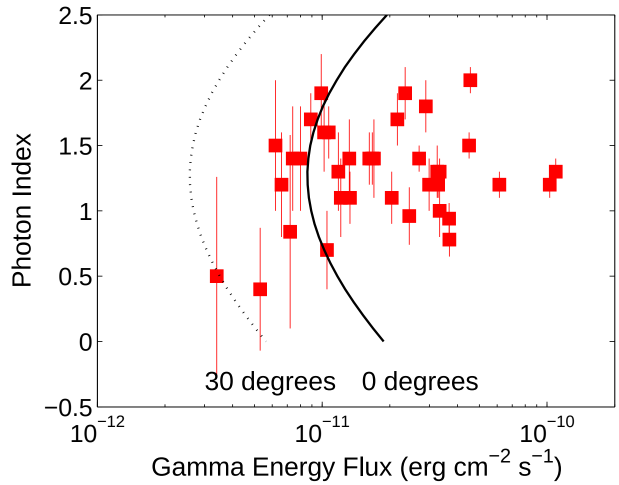


**Figure 1.** Power law index versus gamma-ray energy flux $G_{100}$ for MSPs. The solid line denotes the effective sensitivity curve for pulsar spectra with an exponential cutoff energy of $E_{\rm cutoff} = 2$ GeV at $b = 0^\circ$. The dotted curve is for high-latitude pulsars at $|b| = 30^\circ$.

innermost region. Only 5 out of 40 MSPS are located at $|\ell| < 5^\circ or\ |b| < 5^\circ$, including 3 of the most luminous MSPs in the entire sample. In short, we have not fully resolved the MSP population in the Galactic Centre region.

Assuming a flux threshold of $\approx 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ for a photon index $\Gamma \approx 0.5$ implies that $N_{\rm MSP} \approx 80$ are needed to reproduce the excess GeV emission from the Galactic Centre. For a more conservative estimate, we can take PSR J1600–3053 as a typical representative of the hard-spectrum pulsar population at the Galactic Centre. With a luminosity $L_\gamma = 1.7 \times 10^{33}$ erg s$^{-1}$ and a photon index $\Gamma = 0.4$, PSR J1600-3053 has the hardest pulsar spectrum of the MSPs in the 2FPC (Abdo et al. 2013). A population of comparable luminosity would raise the requirement to $N_{\rm MSP} \approx 3900$. Both estimates are still in agreement with the population of predicted MSPs ($few \times 10^3$) at the Galactic Centre derived from observations at other wavelengths (Deneva, Cordes & Lazio 2009; Wharton et al. 2012).

This does not necessarily imply that all MSPs in the Galactic Centre region will be gamma-ray emitters. Of the 169 known field radio MSPs, about 40 have been detected by *Fermi* (Abdo et al. 2013). Therefore at least 20% of MSPs should be detectable in gamma rays. But at this point, it seems that we have only scratched the tip of iceberg in terms of MSP detections and could be missing the bulk of these systems (Story, Gonthier & Harding 2007).

## 3 NURTURE OR PULSAR ODDITIES?

In terms of luminosity, MSPs appear to be viable explanation for the inner gamma-ray excess. However, we need to further motivate the presence of a population of hard-spectrum MSPs at the Galactic Centre. From a theoretical standpoint, spectral variations are expected in the photon index depending on the viewing geometry and the contribution from different emission regions (Hirotani

2011; Takata, Wang & Cheng 2011). In contrast, annihilating dark matter should be spectrally invariant across the sky.

Our analysis thus far admits two possible MSP scenarios. The first is that *Fermi* is detecting an MSP population that is truly unique to the Galactic Centre. Based on EGRET observations, Wang, Jiang & Cheng (2005) argued that most MSP pulsars near the Galactic Centre are formed from old, slow moving neutron stars that have been recycled to MSPs. Because of its high stellar density ($10^3$–$10^6$ stars pc$^{-3}$), only dense globular clusters ($> 10^3$ stars pc$^{-3}$) with a long dynamical history can come close to mimicking the Galactic Centre neighbourhood. Steady gamma-ray emission has been significantly detected towards a growing population globular clusters (Abdo et al. 2010). These tend to show hard spectral indices ($0.7 < \Gamma < 1.7$) and exponential cutoffs in the range 1.0–2.6 GeV, which go in the right direction to explain the excess GeV emission.

Given the similarities in stellar densities, we want to test whether the Galactic Centre is consistent with the properties of gamma-ray-emitting globular clusters. One of the observational properties of globular clusters that might provide context is the apparent trend for higher gamma-ray luminosity with increasing [Fe/H] for globular clusters (Hui et al. 2011). Figure 2 marks the location where the Galactic Centre falls with respect to the fundamental plane of globular clusters derived by Hui et al. (2011). From the figure, we see that the Galactic Centre appears to be incompatible with the fundamental-plane relationship. Apart from the particular stellar dynamics around the supermassive black hole in the Galactic Centre, the difference may be due to a near solar metallicity of the Galactic Centre [Fe/H] = 0.12 (Ramirez et al. 2000) and the presence of compact young clusters in the central 50 pc that can reach central densities as high as $10^6$ stars pc$^{-3}$ (Figer & Kim 2000). This could be the first tentative indication that we are dealing with an endemic MSP population.

As yet, the formation channels for MSPs remain a puzzle. It is generally agreed that close, interacting X-ray binaries eventually end up as MSPs (Bhattacharya & van den Heuvel 1991). Using population synthesis models, Belczynski & Taam (2004) argued that Roche lobe overflow (RLOF) systems involving the collapse of massive ONeMg white dwarfs should be pervasive in the Galactic Centre. Metal-rich stars fill their Roche lobe more easily (Ivanova 2013), and as a result the formation rate of MSPs could be enhanced compared to globular clusters. This would explain the deviation of the Galactic Centre from the fundamental plane of globular clusters.

As for the hard spectrum measured by Hooper & Linden (2011), we note that the median photon index of the X-ray sources discovered by *Chandra* within the inner $9'$ of the Galaxy is $\Gamma = 0.7$ (Muno et al. 2004a). In the 2FPC, one sees a growing trend $\Gamma \approx \dot{E}^{0.4}$ for harder spectrum at lower MSP spindown luminosity (Abdo et al. 2013). The spindown luminosity can be written

$$\dot{E} \propto (\mu^2 \Omega_*^4 / c^3)(1 + \sin^2 \alpha), \tag{3}$$

where $\mu$ is the dipole moment, $\Omega_*$ is the rotation frequency, and $\alpha$ is the magnetic inclination angle (Spitkovsky 2006). One simple prescription is that the MSP formation process

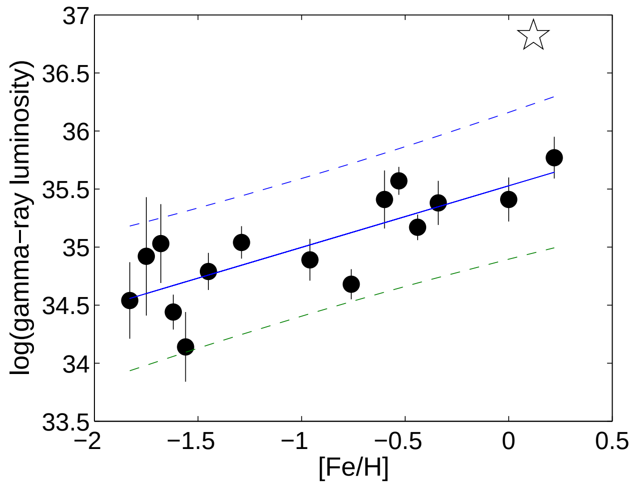


**Figure 2.** Observed gamma-ray luminosity for *Fermi* globular cluster vs. metallicity [Fe/H]. The straight line shows the fundamental plane relationship from Hui et al. (2011). The dashed lines represent 95% confidence bands. The star shows the Galactic Centre, consistent with the tendency for metal-rich environments and higher gamma-ray luminosity but clearly an outlier from the reported relationship.

near the Galactic Centre favours smaller magnetic inclination angles $\alpha \approx 0$. As argued by Johnson, Harding & Venter (2011), this might be a natural tendency for recycled gamma-ray pulsars in general, but could be more frequent in the Galactic Centre. If recycled pulsars with ONeMg companions are prevalent in the Galactic Centre region (Belczynski & Taam 2004), they will be much slower rotators (lower $\dot{E}$) than MSPs with He WD companions (Tauris, Kramer & Langer 2012).

Since there appears to be an emerging population of hard spectra outside the Galactic plane, the alternative scenario is that hard MSPs are not necessarily tied to the Galactic Centre, but have formed throughout the Galaxy. If true, the incipient hard ($\Gamma < 1$) sample might reveal some clues about their origin. Looking at the seven hard *Fermi* pulsars individually, there is a smorgasbord of pulsar oddities. Six of these seven MSPs are in binary systems. PSR J1614–2230 hosts the most massive pulsar known to date (Demorest et al. 2010). PSR J2051–0827 has one of the shortest orbital periods $P_b \approx 2.4$ hr (Stappers et al. 1996), while PSR J2302+4442 has one of the longest $P_b \approx 125.9$ days (Cognard et al. 2011). PSR J1600–3053 is among the best high-precision pulsars known (Ord et al. 2006). PSR J2124–3358 is the lone isolated MSP (Mignani & Becker 2004). PSR J0101–6422 is the only object where simple geometric emission models fail to explain the observed peaks, suggesting that the details of its MSP magnetosphere are more complex than expected (Kerr et al. 2012). Because of frequent encounters and companion exchanges, the Galactic Centre could be more conducive to the production of pulsar oddities. When compared with other field MSPs, no single connecting thread stands out in this bunch. However, we cannot rule out that these systems were formed in rare special environments. Dedicated studies of possible MSP birth locations and companions could reveal additional information.

## 4 IMPLICATIONS AND CONCLUSIONS

In view of our results, it is still possible to explain the gamma-ray excess in the Galactic Centre with a population of hard-spectra MSPs. An essential test of these ideas is to search for similar excesses in other sections of the Galaxy. Interestingly, a possible excess coincident with the *Fermi* bubbles has been reported (Hooper & Slatyer 2013; Huang, Urbano & Xue 2013). Also Ackermann et al. (2012b) indicated that current diffuse gamma-ray models under predict the data in the Galactic plane. It is possible that some of the MSPs discussed here might have migrated to regions adjacent to the Galactic Centre. Even if MSPs are not the culprits of the excess, inverse Compton scattering of diffuse X-ray emission near the Galactic Centre (Muno et al. 2004b) by relativistic electrons (Lorentz factors $\gamma \approx 500$–$1000$) could leave an imprint at GeV energies. A deep Galactic Centre survey with the ability to resolve hard sources planned for the Cherenkov Telescope Array should help clarify this issue (CTA Consortium 2013; Dubus et al. 2013).

It seems clear that modelling the unresolved pulsar distribution will be critical step to assess astrophysical signatures of dark matter. Beyond the Galactic Centre, pulsars above the Galactic plane could potentially mimic Galactic dark matter subhalos (Baltz, Taylor & Wai 2007; Mirabal et al. 2012). Nearby pulsars might also provide a source for the observed rising positron fraction (Grasso et al. 2009; Hooper, Blasi & Serpico 2009). As a result, rather than treating excess GeV emission as evidence for dark matter, it now seems obligatory to start including undetected pulsars as one of the largest contributors to this complex signal (Gordon & Macías 2013). This has been done rather successfully with the diffuse gamma-ray emission from the interstellar medium (Ackermann et al. 2012b). An excellent first attempt to account for pulsars was advanced by Geringer-Sameth & Koushiappas (2012). Since it is not obvious how to include a population that might be generally undetectable to *Fermi* surveys, we must be extremely meticulous in building a composite pulsar template (Hooper et al. 2013). Perhaps it will be found that pulsars and dark matter contribute to the GeV excess. With improved techniques, we could start disentangling the dark signal.

From the data reported so far, it is tempting to conclude that we are starting to see the first signals of annihilating dark matter. But we must take this road with caution in view of the degeneracy with pulsars. Technically, a population of MSPs with steep spectrum would be very difficult to probe in radio (Wharton et al. 2012). The dearth of photons near the LAT sensitivity would also make it very difficult to conduct gamma-ray blind period searches with *Fermi* (Saz Parkinson et al. 2009). None the less, a dedicated search for gamma-ray pulsations from the inner Galaxy is a must (Saz Parkinson 2012). A radio survey for additional pulsars with the next generation of sensitive receivers also appears to be a necessity.

At the end of the day, the strongest astrophysical case for dark matter annihilation will be able to convene multiple sources with the same spectral signature across the sky. A tie-break would be the localisation of "Crab-like" power-law tails in *Fermi* pulsars at energies above 20 GeV with the upcoming Cherenkov Telescope Array (Hassan et al. 2012; de Oña-Wilhelmi et al. 2013). An alternative possibility is the direct detection of a spatially extended dark matter source (Bringmann & Weniger 2012). A line-like gamma-ray feature would be a game point (Bringmann et al. 2012; Weniger 2012; Su & Finkbeiner 2012; Finkbeiner, Su & Weniger 2013; Hektor, Raidal & Tempel 2012; Ackermann et al. 2013). Confirmation in at least two pillars of dark matter detection clinches the game (Bauer et al. 2013). However, indirect dark matter detection may prove much more subtle. Observing the Galactic Centre more frequently as part of a renewed *Fermi* observing strategy could start to break the stalemate (Weniger et al. 2013).

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