Young Pulsars and the Galactic Center GeV Gamma-ray Excess

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Studies of Fermi data indicate an excess of GeV gamma rays around the Galactic center (GC), possibly due to dark matter. We show that young gamma-ray pulsars can yield a similar signal. First, a high concentration of GC supernovae naturally leads to a population of kicked pulsars symmetric about the GC. Second, while very-young pulsars with soft spectra reside near the Galactic plane, pulsars with spectra that have hardened with age accumulate at larger angles. This combination, including unresolved foreground pulsars, traces the morphology and spectrum of the Excess.

Introduction.— The Fermi Large Area Telescope [1] has transformed GeV gamma-ray astrophysics. Pulsar physics in particular has experienced an enormous advance [2]. The impact is much greater than even the impressive increase in the number of gamma-ray pulsars, from 7 pre-Fermi to >170 now [3,4], alone suggests. GeV detections of old, recycled millisecond pulsars (MSPs) went from zero to ~60 in under six years. The >100 detections of young pulsars (τ < Myr) imply ubiquitous GeV emission [5,6], with the radio-quiet population now at ~40 from a lone prototypical member, Geminga [7,8].

Fermi could also fulfill the long-standing hope of detecting gamma rays from the annihilation or decay of dark matter [9-14], which comprises ≈ 84% of all matter [15,16]. A number of groups [17-29] have used Fermi data to search for a signal originating from around the Galactic center (GC), where this flux should be largest. The exciting recent development from these studies is the measurement of an extended excess of GeV gamma rays above model predictions peaking from 1–3 GeV. The Excess spectrum is reasonably fit by the annihilation of a 30–60 GeV dark matter particle [e.g.,19,45], though the angular intensity implies a density profile steeper than often extrapolated from simulations.

The great challenge is to determine whether this signal indeed arises from dark matter or is due to an unaccounted-for source of gamma rays. One suggestion is a contribution from MSPs [20,46,48], which have a similar spectral shape as the Excess in gamma rays and are expected to exist there at some level [49]. It has been argued that MSPs cannot match the Excess [50,51] and uncertainties in MSP formation make definite predictions difficult.

We show that young pulsars from the GC itself produce a diffuse GeV flux that has been widely underestimated. Such pulsars arise from core-collapse supernova explosions of short-lived massive stars. Their birthplaces thus tend to trace star formation. The GC is the most concentrated star forming region in the Milky Way (MW); the inner ~ 200 pc central molecular zone (CMZ) accounts for 5–10% of the current Galactic star formation rate [e.g.,52,53]. Further, the CMZ contains an estimated ~13% of all MW Wolf rayet stars [54,55]; these evolved, >25 M_☉ stars are near explosion and may remain from an even more intense recent period of star formation [e.g.,60]. This implies a substantial, ongoing production of pulsars, with birth kicks leading to a continuous, symmetrical distribution centered on the GC.

Fig. 1 displays a second piece to this puzzle. Here we compare the gamma-ray spectrum measured from Geminga, the best characterized of radio-quiet pulsars, to that expected from 35 GeV dark matter annihilating to a b-quark pair [62] as proposed for the Excess. The striking similarity to the Excess is a consequence of the hardening of gamma-ray pulsar spectra with decreasing spin-down power (Ė) as seen in Fermi data [3,64].

FIG. 1: A comparison of phase-averaged Fermi gamma-ray data of Geminga [52] to our spectral shape from pulsars within 5° of the GC and > 2° from the disk (see text), which resemble that from 35 GeV dark matter particles annihilating to b̄b as proposed to explain the GC Excess [23].
Very young, high-$\dot{E}$ pulsars with soft spectra then reside within the Galactic plane, where they are masked or subtracted as point sources and do not contribute to the observed Excess. On the other hand, pulsars old enough to reach large angles have hard spectra (Geminga has a characteristic age of $\sim 3 \times 10^7$ yr). Fermi has also shown that the gamma-ray luminosity, $L_\gamma \propto \dot{E}^{1/2}$, declines much more slowly than spin-down power, while gamma-ray efficiency, $L_\gamma/\dot{E}$, rises at low $\dot{E}$ [3]. Since an additional 20% of Galactic star formation occurs within a projected radius of 15° of the GC [65], there should be unresolved high-latitude disk pulsars that also contribute to the Excess. Indeed, $\sim 15\%$ of all radio pulsars are seen in this region [66].

Our conservative estimates suggest the population of unresolved young pulsars may constitute a significant fraction, if not all, of the excess GeV gamma rays. Thanks to intensive Fermi and radio studies, we are able to forward model the emission of young pulsars. This is in contrast to modeling MSPs, which have complicated formation channels, or ancient cosmic-ray bursts [67-68] or dark matter which have a large range of free parameters. We do not include any MSP or other non-young-pulsar contribution in this work. We discuss a few of the many implications here and in a companion paper [69].

The GC pulsar factory.— We use a suite of Monte Carlo simulations to forward model the present day distribution of ordinary young pulsars throughout the GC and Galactic disk. Our methods largely follow Refs. [70] and [5], who successfully reproduced the observed distribution of nearby radio and gamma-ray pulsars, respectively. We extend both by including the CMZ contribution (avoiding here the peculiar central parsec [71]).

To generate our simulated gamma-ray pulsar population, we select the pulsars’ ages randomly assuming a constant birth rate of $2.1 \times 10^{-2}$ yr$^{-1}$ in the disk [70,72], formed on circular orbits within the MW spiral arms [70].

The GC rate depends on the number of massive stars formed over the previous $\sim 30$ Myr, due to their finite ages [73], while the present star formation rate may be near a minimum if episodic on $\sim 10$ Myr periods [92]. Over this time their positions will be symmetrized by cluster dispersion and differential rotation. For simplicity, we assume a constant birth rate of $1.5 \times 10^{-3}$ yr$^{-1}$ in the CMZ, $\approx 7\%$ of the Galactic rate. These pulsars are formed from a spherical isothermal distribution ($n \propto r^{-2}$), between 20 and 200 pc of Sgr A* – the region of most GC star formation.

We kick each pulsar by selecting a random kick velocity from a three-dimensional normal distribution with a mean velocity of $\approx 408$ km s$^{-1}$ [74]. Each pulsar orbit is integrated over its lifetime using GALPY [106] with the MWPotential2014 model for the Galactic potential [75].

The pulsar gamma-ray luminosity depends on its total spin-down power, which in our models is determined by the surface magnetic field, initial spin period, and age. We do not include any MSP or other non-young-pulsar contribution in this work. We discuss a few of the many implications here and in a companion paper [69].

We assign each pulsar a constant surface $B$ from a log-normal distribution with mean $(\log_{10} B) = 12.65$ and $\sigma_{\log B} = 0.45$. The variance in the magnetic fields is roughly between those used by Refs. [70] & [5]. The pulsars are born with an initial spin period, $P_0$ following [5]. Therefore the spin-down luminosity of the pulsar $\dot{E} = 4\pi^2 I \dot{P} P^{-3}$, where $I = 1 \times 10^{45}$ g cm$^2$ is the pulsar moment of inertia, $\dot{P} = 8\pi^2 R^6 B^2/3I c^3 P$, $R = 10^6$ cm is the radius of the pulsar, $c$ is the speed of light, and $P = (P_0^2 + 16\pi^2 R^6 B^2/3 I c^3)^{1/2}$.

Gamma rays in excess.— Fermi observations of young pulsars show that their sky-averaged gamma-ray luminosity follows a trend that agrees with the theoretically expected $L_\gamma \propto \dot{E}^{1/2}$ [e.g., 3,5], although with notable scatter. We normalize $L_\gamma$ for each pulsar as

$$L_\gamma = C \left( \frac{\dot{E}}{10^{33} \text{erg/s}} \right)^{1/2} \times 10^{33} \text{erg/s}. \quad (1)$$

The heuristic value of $C = 1.0$ [3,5] underestimates the luminosity of Geminga by a factor of 5, and the mean and median gamma-ray luminosity of ordinary pulsars found in [3] by a factor of $\approx 3$. For a given pulsar, models predict different beaming corrections to the observed flux dependent upon the angle to the observer and magnetic field alignment [78]. Using the beaming-corrected relations of [64] modeled from many individual light curves, we find that the mean luminosity is $C = 2.2$, after removing the top and bottom 5% of the sample. Here, we...
are mostly concerned with a population-averaged luminosity density and take a fiducial value of $C = 1.3$, which produces one-third of the unassociated plane sources in the \textit{Fermi} 3FGL catalog \cite{79}. For simplicity, we assume that gamma-ray emission turns off at $\dot{E} \lesssim 10^{33.5}$ erg s$^{-1}$, higher than the outer gap death line of \cite{80, 81}.

In Fig. 2, we show the gamma-ray fluxes of a single realization of the unresolved gamma-ray pulsars towards the GC. The flux is centrally concentrated around the CMZ, but outside of the central few degrees, pulsars in the Galactic disk become the dominant component, with a population of point sources extending well above the Galactic plane. The outermost regions are the most impacted by Poisson fluctuations in the underlying pulsar population, and show the greatest amount of asphericity. Since most of the flux in the inner 5° comes from the CMZ pulsars, flux-weighted measures of the asymmetry of the emission will not be heavily impacted by the disk.

In Fig. 3 we show the surface brightness map of a single realization of the unresolved gamma-ray pulsars towards the GC, the unassociated plane sources in the \textit{Fermi} 3FGL catalog \cite{79}. For simplicity, we assume that gamma-ray emission turns off at $\dot{E} \lesssim 10^{33.5}$ erg s$^{-1}$ (solid red line) the range of unassociated plane sources between $|b| < 20^\circ$ and $|l| < 20^\circ$ \cite{77}.

\begin{equation}
L_{\text{ps}} = 1 \times 10^{-10} \frac{1^\circ}{(b^2 + (3e^2))^{1/2}} \text{ erg s}^{-1} \text{ cm}^{-2},
\end{equation}

where $b$ is the Galactic latitude in degrees, as shown in Fig. 2. We use 2FGL only to be consistent with \cite{25, 27}.

In Fig. 3 we show the surface brightness map of young pulsars to the gamma-ray excess at 2 GeV reported by Daylan et al. \cite{25} and Calore et al. \cite{27, 28}. The solid red line shows the mean surface brightness of the pulsars using concentric rings with 1° width that exclude the Galactic plane (at $|b| < 2^\circ$), motivated by comparison with \cite{25}, while the green dashed line includes only the high-latitude pulsars ($|b| > |l|$ and $|b| > 2^\circ$).

We see that the total flux of the young pulsars can plausibly explain much of the GeV Excess in the region we explore in this work, with a slope well within the literature range. Since pulsar behavior near the gamma-ray death line remains unclear, as is the underlying magnetic field distribution of the pulsars, we have chosen to plot along with the total flux implied by Eq. (1) down to $\dot{E} > 10^{33.5}$ erg s$^{-1}$ (solid red line) the range of uncertainty of the underlying model (gray band). We have done this by varying the main parameters within the empirically observed limits. We have varied $C$ between $10^{34} \lesssim \dot{E} \lesssim 10^{37}$ erg s$^{-1}$, $0.55 \lesssim \sigma_{\log B} \lesssim 0.30$, and $2.2 \lesssim C \lesssim 1.0$. Currently, the lowest $\dot{E}$ for a young gamma-ray pulsar is $\sim 3 \times 10^{33}$ erg s$^{-1}$ \cite{3}. Unfortunately, low-$\dot{E}$ radio-quiet pulsars often lack distances (thus luminosities). Indeed, tests coupling both local observations and the large-GC angle pulsar population may improve our understanding of these faintest pulsars \cite{3, 75, 83}.

The inferred spectrum of the Excess mostly comes from the $\sim 5^\circ$ region around the GC \cite{25, 28}. In our model, the luminosity from this region is dominated by Geminga-like pulsars (which has $\dot{E} \approx 10^{34.5}$ erg s$^{-1}$). Fig. 1 shows the flux-weighted spectrum of all pulsars that are beyond the plane ($|b| > 2^\circ$) and within $5^\circ$ of the GC, which is comparable to the Excess spectral shape near the peak. Note that $\gtrsim 10$ GeV pulsar emission may be underestimated by using an exponential cut-off \cite[e.g.,][]{3, 51, 69}.
FIG. 4: Intensity of 2 GeV backgrounds as a function of angular separation from the Galactic Center. The solid red line shows the average pulsar contribution from our fiducial model, obtained from angular rings (excluding the $|b| < 2^\circ$ disk), with the gray shaded region showing the systematic uncertainty in the gamma-ray pulsar population. The green dashed line is only from pulsars at high Galactic latitude ($|b| > |l|$ and $|b| > 2^\circ$). Also shown are intensities of the gamma-ray Excess, from Ref. [25] which used Gaussian angular rings (masking $|b| < 2^\circ$) out to $\approx 10^\circ$ (black points and error bars; the lower point at $5^\circ$ is their “Full Sky”, similar to their “Galactic Center” values) and Ref. [28] (shaded blue bands) which assume a fixed profile shape.

**Discussion.**—We have shown that a population of young ordinary pulsars originating in the central molecular zone of the Galactic center and the Galactic disk naturally produces a gamma-ray spectrum, amplitude, and spatial distribution resembling the observed GeV excess in the Galactic center. Our model uses the observed properties of radio [70, 74] and gamma-ray pulsars [3] to estimate their gamma-ray flux. The young pulsar luminosity profile is then determined by kicked pulsars evolving with age, while we include no contribution from millisecond pulsars.

Calore et al. [28] found that the Excess brightness varied between different analyses at the $3-\sigma$ level, suggesting at least a factor of two uncertainty in its absolute normalization. In this work, we used a common, simplified model for pulsar evolution. This model also has a factor of two uncertainty due to discrepancies in the preferred surface magnetic fields for radio pulsars and gamma-ray pulsars, pulsar behavior near the gamma-ray death line, and the GC SN rate (though our fiducial value is near that preferred in Fermi Bubble models [84, 85]). We discuss these in [69], although we note here that the parameters used by our models were specifically optimized to reproduce the currently observed distribution of pulsars.

Nevertheless, there remains much room for improvement. While current “gap” models of pulsar emission [e.g., 89, 90] work reasonably well [64], ab initio models under development promise better physical understanding [91, 94]. Ideally, we would also have a similar understanding of neutron star birth kicks, spins, masses, and magnetic fields [95–98].

We discuss further observations to help determine the young pulsar fraction in [69]. These include the pulsar contribution to a similar GeV excess seen along the Galactic disk [90], which may also be evident as residual emission in the inner Galaxy [29]. We have not here included electrons and positrons from pulsar winds (e.g., Geminga displays diffuse TeV emission [100] due to $e^\pm$ [101]). If proportional to $\dot{E}$, most of the output is concentrated near the plane to yield an inverse Compton flux (as may be needed in the inner galaxy [27, 29]).

Despite present uncertainties, young pulsars must be accounted for in future models of the Excess, with our conservative estimates suggesting that they constitute a substantial fraction. If the Excess extends to higher energies, as in [28], and if pulsars only contribute a fraction at GeV energies, a higher-mass dark matter candidate may yet be present (see [69]). Unlike the GC, old dwarf galaxies should not contain young pulsars, so improved gamma-ray studies [14, 102] will help our understanding of both the Excess and pulsar physics. Clearly, additional Fermi data will be vital to resolve more sources, characterize pulsars, and accumulate statistics at the highest energies, where upcoming IACTs will also be relevant [103, 105], to dissect the Excess.

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