

Ilias Cholis, 19/7/2022 **In collaboration with Tess Hoover (OU) and Iason Krommydas (NTUA)** *Cholis, Krommydas, PRD 105 023015 (2022)*

Milky Way Pulsars as sources of high-energy cosmic rays as (see e.g. $[24]$):
 $\frac{E_{tot}(t)}{2} = -12\frac{2}{0} - \frac{1}{1 + \frac{t}{1 + \alpha}}$

Crab (very young pulsar 10^3 yr) where t_5 is the time in units of 10^5 years. \vec{B} reformed, the total energy that a mature pulsar (the \vec{B} the form of the MI madipulsars innse i

is the period of the star in seconds. With time and can be modeled as, χ Ω of the spin-down according to mature pulsar, we also have that $\Omega_0 \approx \Omega(t/\tau_0)$ measured today. For instance, for the Geminga pulsar $(P = 230 - 8 + 1 \approx 3$

2 arcmin a single pulsar. Qualitatively, the comptrements of a declining absolute luminosity escape probability6coaspire in singling out to consecuted to contribute maximally dipôgoâspire in strathanna. where to the positron flux.

 (c)

⁰° years. Bhgréfqie, the total energy that
Pulsars loose their spinning energy into EM radiation and cosmic rays. where $B_{12} = \mathbb{B}_s/10^{12}\text{G}$ is the magnethis "spin-down" power evolves $\mathbb{R}_1^2\mathbb{R}_1^2$ Se their spinning energy 2 radiaแon and cosmic
iก-d'own" power evolv ino.nG

 $k + 1$

100 kg 30 kg

 $10 \ \rm{Jyr}$

 3 ky

 $\dot{E}(t) = \dot{E_0}$ ✓ 1 *t* $\frac{1}{\sqrt{2}}$ $\sqrt{\frac{\kappa+1}{\kappa-1}}$ $\mathcal{A}(\mathbb{H}/\mathbb{H})$ $B_{12} = 1.6$ and $R_{10} = 1.5$ \ldots has \ldots \ldots output of the optical (ESO) $E(t) = E_{0,\text{per}}$. It for $\ket{1}$ is worth stressing, however, that only a small fraction of this \mathcal{T}_0 / \langle , will eve e lectron Φ ositron pairs, and thus the pair umber showled be the pathology and absolute 300 kyr $1\,\mathrm{M}_{\odot}$ 3 Myr $1₁$ 10 Myr $\bigcup\limits_{i=1}^n\mathcal{C}_i$ *m*

synchrotron pulse $s = 10$, $s = 1000$ $s = 2500$ is the star with \odot ¹⁰ ¹⁰⁰ ¹⁰⁰⁰ ¹⁰⁴ 0.01

the initial spin frequency of the pulsar and Po is the initial gevried. Nume To proceed in a more quantitative way towards the calculation of the over needs to adopt a model for the $e^+ - e^-$ acceleration and escape probability from field, period, etc. and then integrate over a Monte Carlo distribution of these portulation. The resulting injection spectrum we adopt follows from such a calculation in Ref. [18]: In Ref. [18]: α calculation in Ref. [18]: In Ref May Covards the calculation of the over \mathbf{E}_{u} (GeV) Fig. 1: Time evolution of the Earth from pulsar at a distance of 1 kpc with the distance of 1 kpc in the \mathcal{M} index n \mathcal{M} in the 1.6, and an injection cutoff M = 1.6, and an injection cutoff M

amma-Rays / Neutron Star dN_e $\approx 8.6 \times 10^{38} N_{100} (E_e/{\rm GeV})^{-1.6} \exp(-E_e/80 \,{\rm GeV})$ dN_e $\mathcal{L} = \mathcal{L}$ diffusion and energy loss are described in Sec. II A. Gamma-Rays

Through many different observations Pulsars are known sources of cosmic-ray electrons and positrons on is the rate of pulsar formation in units of pulsars per century. The dE_e energy output in electron-positron pairs of approximately 6×10^{46} erg per p I hrough many different observations Pulsars are known sources of cosmic-ray $f(x) = \sqrt{\frac{E}{E}} \left(\frac{E}{E} \right)$

Milky Way Pulsars as sources of high-energy cosmic rays as (see e.g. [24])
Milky Way Pulsars as sources of high-energy cosmic rays

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Pulsars loose the Pulsars loose their spinning energy where $B_{12} = \mathbb{B}_s/10^{12}\text{G}$ is the magnethis "spin-down" power evolves $\mathbb{R}^2\mathbb{R}^2$ into EM radiation and cosmic rays. **9** radiation and cosmic
in-down" power evolv This "spin-down" power evolves with time and can be modeled as,

 $\sqrt{\frac{1}{\gamma_0}}$ measured today. For instance, for the Geminga pulsar $(P = 230 - \frac{\kappa + 1}{\kappa - 10})$ $B_{12} = 1.6$ and $R_{10} = 1.6$ \ldots $R_{\rm T} = 10000$ \ldots \ldots \ldots \ldots \ldots \ldots output of the p_pixel (ESO) $\epsilon = E_0 \sqrt{1 + \left(\frac{1}{\epsilon}\right)^2}$ and ϵ 100 kyr 30 kyr $300 \, \mathrm{k}$ $1 \, \mathrm{Myr}$ 3 Myr $1₁$ 10 Myr $\bigcup\limits_{i=1}^n C_i$ *m* $\dot{E}(t) = \dot{E_0}$ γ 1 MW *t* $\mathcal{T} _0$ $\sqrt{\frac{\kappa+1}{\kappa-1}}$

 $\frac{1}{3}$ and $\frac{1}{3}$ $\frac{1}{3$ the initial spin from flux, of the pulsar single pulsar over a time $t \gg \tau_0$ under τ_0 To proceed in a more quantitation it in the calculation of kinetic energy. The overall spectrum from Galactic pulsars, α needs to adopt a model for the e^{+15} e^{-15} acceleration and escape probability from a given magnetic pulsar with a given magnetic field, period, etc. and then integrate over a Monte Carlo distribution of these possible the resulting injection spectrum we E (pt follows for L quch a calculation in Ref. α in Ref. [18]: α is its initial rotational kinetic energy: *E* FIG. The Carlo distribution of these F_a \sim $F_a = I_a Q_a^2$ in si E_{tot} in \simeq E_0 = 15 I_0 Ω_0 uch a cutoff E_0 $\frac{1}{2}$ 2 $I_0 \Omega_0^2$

 $\mathcal{A}(\mathbb{H}/\mathbb{H})$

 3 ky

 10 yr

 dE_e $\approx 8.6 \times 10^{38} \dot{N}_{100} \left(E_e/{\rm GeV}\right)^{-1.6} \exp{(-E_e/80 \, {\rm GeV})}$ electrons and positrons. is the rate of pulsar formation in units of pulsars per century. The energy output in electron-positron pairs of approximately 6×10^{46} erg per p I_{C} gamma-rays, which is the presence of dE_e *Through many different observations Pulsars are known sources of cosmic-ray* $f(x) = \sqrt{\frac{E}{E}} \left(\frac{E}{E} \right)$

 dN_e assume the delta-function dN_e

 σ **RdN**

 dN_e

lod of the star in seconds the period \boldsymbol{F} explained by a population of gamma-ray pulsars. Here, \mathbf{H} and the paper of the phrase \mathbb{Z} throughout the phrase \mathbb{Z} of pulsars in Sec. II, we turn our attention in Sec. II, we have a rate given by $\mathbf{$ of the Galactic Center, as opposed to the much smaller dio and gamma-ray wavelengths. When in initially formed, when in initially formed, when in the control of the control **ulisars the community of the late of enders whenever** $\mathbf{M} \mathbf{M} \cap \mathbf{M} = P - 33 \times 10^{-15} (B/10)$ \mathbf{N} is the strength strength strength strength strengths \mathbf{N} $A = \langle \cdot \rangle$ and $A = \sqrt{1 + 4}$ (recycled) pulsars: NEE-D $\dot{E} = \frac{\tau_0}{\tau_0} \frac{B_s^2}{B_s^2}$ $^2_sR^6_s$ $\frac{6}{s}$ k) 4 $\frac{16.842 \times 10^{12}}{6c^3} \approx 10^{33} \frac{1}{2}$ $^{24}_{12}R_{1}^{\ell}$ \oint_{10} \oint_{10} $\frac{1410}{9}$ $\frac{1}{9}$ $\frac{0}{8}$ $\frac{1}{10}$ $\dot{P} = \dot{P} = 3.3 \times 10^{-15} (B/10^{12} \text{ C})^2 (D/0.3 \text{ s})^{-1}$ UUNIFANIV is the p.0 \land 10 $(D/10$ U) $(I/0.05)$ 1-down, according to ^Ω(t) = ^Ω⁰ $\frac{1}{11}$ $\tau_0 = \dot{P}$ = 3.3 × 10⁻¹⁵ \overline{u} (\overline{L} <u>ND</u> $(10^{12} \text{ G})^2 (P/0.3 \text{ s})^{-1}$ $\tau_0 \rightarrow 7 R_s^2 R_s^6 \Omega^4 0^{7} B_{123}^{-2}$ $\frac{120 \text{ U} \text{in } QN_s}{1231 \text{ D}24 \text{ b}4}$ $3.4R_{\odot}^{\prime}$ $R_{10}^{-4}P_0^2$ years It follows that tr tr tr limit to the rate of energy deposit in the form of electron- $L = 1000 D / 10$ U $/$ (1) .
7940 $\overline{}$. $3.3 \times 10^{-15} (B/10^{12})$ 10° $\overline{\mathcal{P}}$ **COMPANION**⁷⁰ = 3.3 × 10⁻¹⁵ ($B/10^{12}$ G)² ($P/0.3$ s)⁻¹ α -gown, according to the discrete to $\dot{E} =$ $r = -\frac{1}{6c^3} \approx 10 \text{ V} \frac{1}{2} \frac{1}{4} \text{ eV} \text{ erg s}$ \mathbf{A}_i , and \mathbf{B}_i is the most relevant aspect of the most relevant aspects relevant aspects \mathbf{A}_i to the gamma-ray spectra observed from \mathcal{C} $\frac{53}{6}$ $\frac{123}{8}$ $\frac{1}{10}$ $\frac{1231}{124}$ $\frac{124}{12}$ $\frac{10^{10}}{10}$ $\frac{10^{10}}{10}$ $\frac{10^{10}}{10}$ $\frac{9}{10}$ $6c³$ and $12¹⁰$ e of energy deposit in the form of elect $\frac{2}{2}$ = 42*IP =* $\frac{1}{4}$ *F*⁹⁴*D* $\frac{1}{2}$, 3² der of the second of m milliseconds, $\vec{\tau}_0$ \mathbf{F} . The magnetic magnetic brake \mathbf{F} of \mathbf{F} and \mathbf{F} and \mathbf{F} are bracking, and \mathbf{F} ³*.*³ ¹⁰¹⁵ (*B/*10¹² G)² (*P/*0*.*3 s)¹, corresponding to e stantin seconds. The period P (gyration frequency, M) increases

, (1)

Modeling the Pulsars

The pulsar spins down with $\tau_0 \sim 10$ kyr $<<$ *Time for cosmic rays to propagate to us.*

Pulsars are ~Time-bombs of Cosmic-Rays

While pulsars are not the only source of cosmic-ray electrons and positrons, adding their contribution we can test various hypotheses on the properties $\frac{1}{10}$ 0.1 of Milky Way pulsars using the recently released (2017-2021) cosmicray energy spectral measurements.

Study the Pulsar Properties through the Observed Cosmic-Ray Spectra

- The Neutron Stars distribution in space
- The initial conditions of the Neutron Stars (as a distribution of properties) in terms of their initial spin-down power
- The uncertainties on their time evolution, i.e. κ $\&$ τ_0
- How many cosmic-ray electrons and positrons they produce/inject into the interstellar medium and with what spectrum
- How these electrons/positrons propagate from there to us (ISM physics & Heliospheric Physics)

We have produced over 7K unique Milky-Way pulsar simulations. Each simulation contains anywhere between 5K to 18K unique pulsars within 4 kpc from the Sun.

The impact of ISM assumptions on the propagation of cosmic-rays

Cholis, Krommydas, PRD 105 023015 (2022)

Alternative assumptions on the (i.e. observable) luminosity of pulsars

Cholis, Karwal, Kamionkowski, PRD 98 063008 (2018)

Total Lepton Flux from AMS-02: *Cholis, Krommydas, PRD 105 023015 (2022)*

Total Lepton Flux from DAMPE (probing the youngest pulsars):

Total Lepton Flux from DAMPE (probing the youngest pulsars):

Cholis, Krommydas, PRD 105 023015 (2022)

The impact on ISM assumptions

We can also invert the question on what we can learn about the ISM if pulsars are prominent sources of cosmic-ray electrons and positrons:

Next Goal: Pulsars VS Dark Matter

Technique to Differentiate: Power-Spectrum on the *Cosmic-Ray Spectrum*

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Cholis, Hoover (in prep. 2022)

Performing Cross-correlation of electrons and positrons

Conclusions and what comes next

- Performed simulations on the Milky Way pulsars population, accounting for the various astrophysical modeling uncertainties.
- Tested simulations to recent cosmic-ray measurements to probe the averaged properties of pulsars at times well after EM observations are sensitive to provide us information on their evolution
- $\bullet\,$ We find clear preference for braking index $\,\,\kappa\geq 3$
- We find that pulsars have quite uniform properties as sources of cosmicray electrons and positrons (fraction of E and spectrum) and likely release of $O(10\%)$ of their rotational energy to cosmic-rays in the ISM.
- We find at ~12 GeV an interesting spectral feature that suggests a new subpopulation of sources at (contribution from inner spiral arm or from dark matter)
- Early Stages of performing power-spectral calculations (auto-correlation)
- Cross-correlating the electron and the positron energy spectra for coinciding features in the measurements (we find some first hints)

Additional Slides

Power-Spectrum on the Cosmic-Ray Spectrum Is it a robust Test?

Cholis, Karwal, Kamionkowski, 2017

Power-Spectrum on the Cosmic-Ray Spectrum Is it a robust Test? Probably Yes.

Cholis, Karwal, Kamionkowski, 2017

On the ~12 GeV feature:

 -20

Preliminary

 $\dot{0}$

 $\Delta \chi^2$

 10

On the ~12 GeV feature:

Preliminary

$$
-15 -10 -5 0 5 10 15
$$