The Cosmic-Ray Positron Excess: Status of the Pulsar Explanation

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Introduction

The HAWC collaboration observations of the TeV halos, which are associated with nearby pulsars, (magnetized spinning neutron stars), indicate that these objects inject significant fluxes of very high-energy electron-positrons pairs into the interstellar medium (ISM), thereby likely providing the dominant contribution to the cosmic-ray positron flux/fraction [1-4]. This fraction, the ratio of the *flux* of positrons to the combined flux of electrons plus positrons present in the ISM, can be used to constrain characteristics of the local pulsar population for many free parameters [5,6]. In building upon previous work done by Hooper, Lindon, and collaborators, the following results of this poster seek to provide further motivation for the pulsar explanation through comparisons of positron flux contributions to the updated AMS-02 data for reasonable parameter choices. Also, these results will serve to update the constraints of the local pulsar population characteristics themselves assuming the pulsar explanation [5-7].

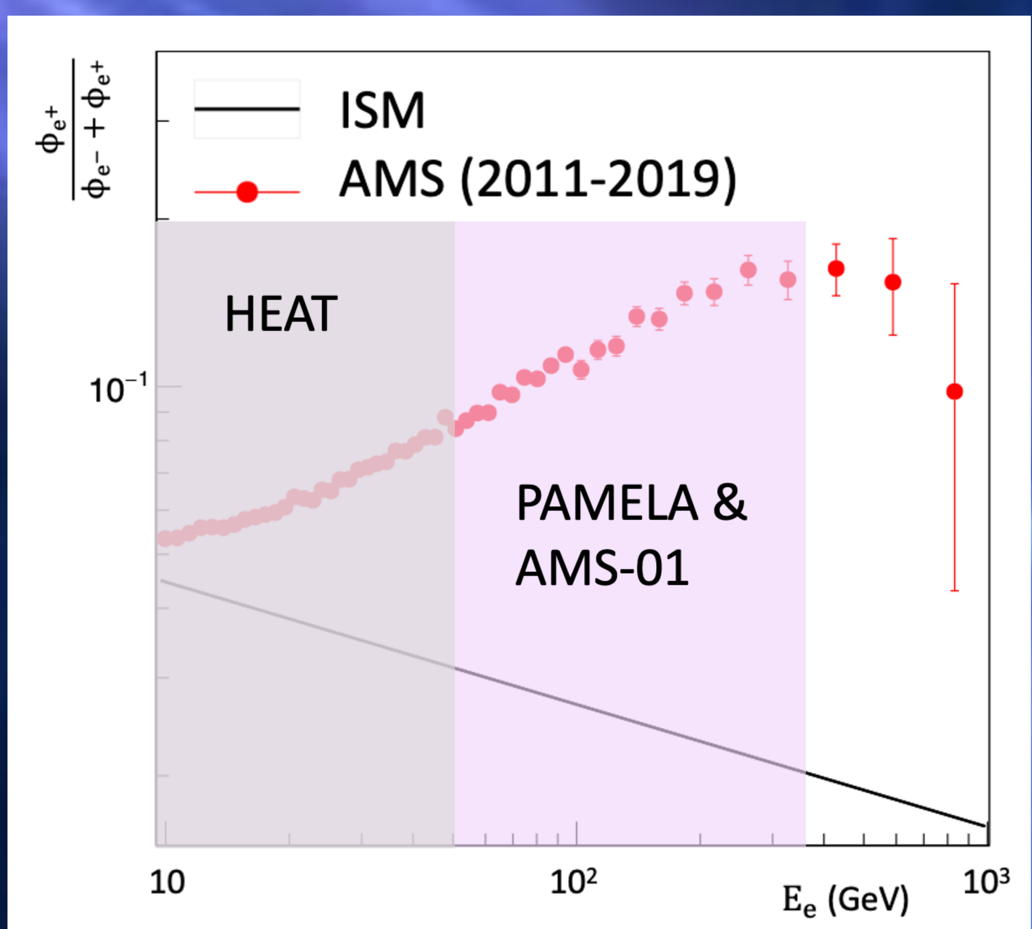

Figure 1: (Above)
Plot to the left shows the primary observations from AMS-02 as the red data points, the secondary predictions from the ISM in the solid black line, and the parameter space probed by previous experiments that first noticed the positron excess in the vertical shaded regions for HEAT (in grey) and PAMELA and AMS-01 (in lilac).

Background

Earlier observations of the positron excess as shown in figure 1, *could* still be explained with annihilating Dark Matter models [8]. However, with better statistics and with the tension more noticeable up to ~ TeV, this scenario has now been largely disfavored and currently, the best explanation involves contributions from pulsars.

High energy positrons and electrons are injected into the ISM from pulsars, emitting gamma rays through inverse Compton scattering and synchrotron radiation [5,6]. It causes the injected electrons and positrons to loss energy, impacting their observed spectrum as seen on Earth. This spectrum can be extracted via the standard propagation

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,r,t) = \vec{\nabla}\cdot\left[D(E_e)\vec{\nabla}\frac{dn_e}{dE_e}(E_e,r,t)\right] + \frac{\partial}{\partial E_e}\left[\frac{dE_e}{dt}(E_e,r)\frac{dn_e}{dE_e}(E_e,r,t)\right] + \delta(r)Q(E_e,t) \qquad (1.1)$$

The differential number density term from equation 1.1 is most useful to describe the distribution of a single pulsar source [6]. For the purpose of this study, these are Monte Carlo simulations (MC) that give both the distance of an MC source from Earth as well as its age. Described by:

$$\frac{dn_e}{dE_e}(E_e,r,t) = \frac{Q_o E_o^{2-\alpha}}{8\pi^{3/2}E_e^2 L_{\mathrm{dif}}^3(E_e,t)}\exp\left[\frac{-E_o}{E_c}\right]\exp\left[\frac{-r^2}{4L_{\mathrm{dif}}^2(E_e,t)}\right] \qquad (1.2)$$

where one can extract the pulsar contribution to the positron flux ratio for many free parameters [6].

These parameters constitute the characteristics exhibited by pulsar sources, both known and catalogued in the Australia Telescope National Facility (ATNF) and unknown simulated Monte Carlo realizations (MC) [9]. The top four most studied free parameters that can affect the pulsar contribution are: (see publication for full list of free parameters)

- **Spin-down Time**: time between injections of particles into the ISM.
- **Spectral Index**: indicator of particle flux density in the power-law distribution.
- **Magnetic Field**: magnitude in the ISM and contributing to energy losses.
- **Pulsar Injection Time**: time at which we start to allow for pulsar injection.

Results

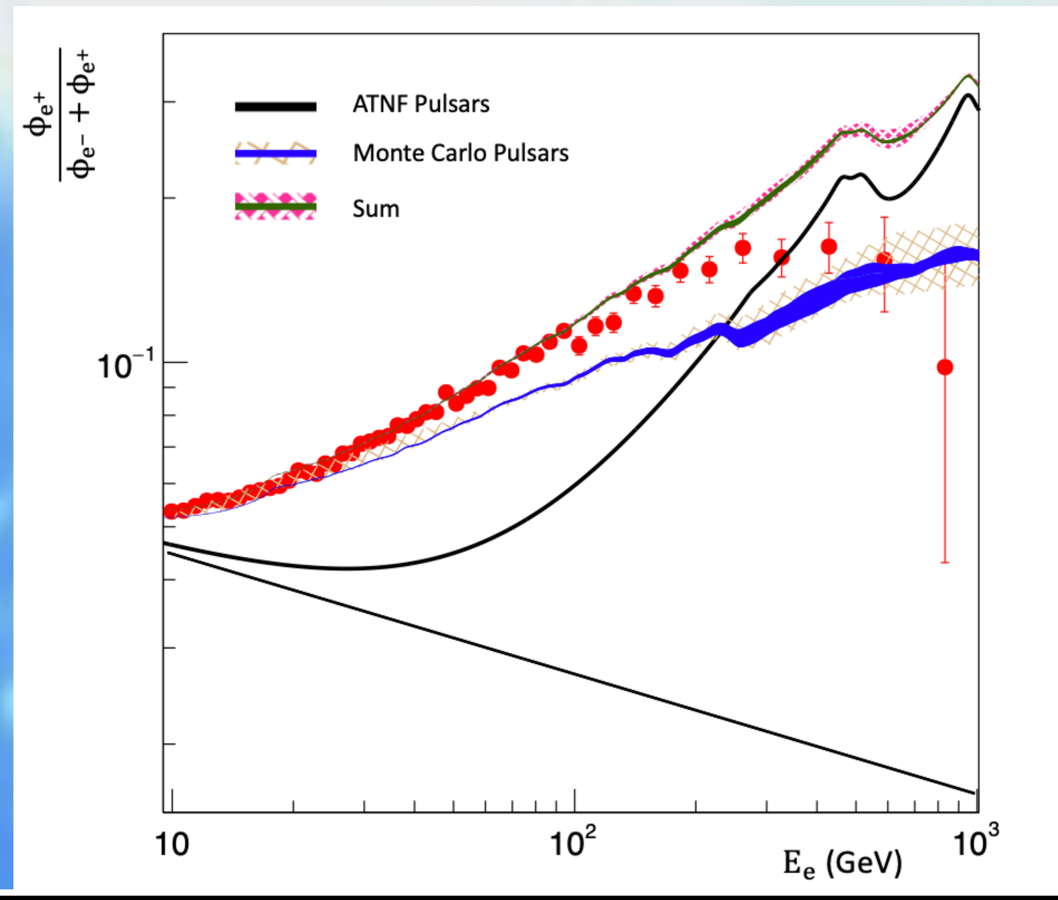

Figure 2: (Above)
Positron fraction from the pulsars in the ATNF catalog (thin black line), from unknown pulsars as calculated by our Monte Carlo (orange cross-hatch), and from the sum of these contributions (magenta weave). The middle solid blue and dark green bands indicate the one sigma regime within the total distribution bands for unknown and sum respectively. In this figure, we have adopted the following parameters: α = 1.5, η = 0.15, τ = 10^4 yr, B_{ISM} = 3 μG, and t_{PWN} = 3 x 10^4 yr. The solid (shaded) bands around the blue and orange curves reflect the variation observed across 68% (all) of the realizations of our Monte Carlo. Note: this parameter choice was chosen based upon the overall best fit given all free parameters in our initial study (Default case).

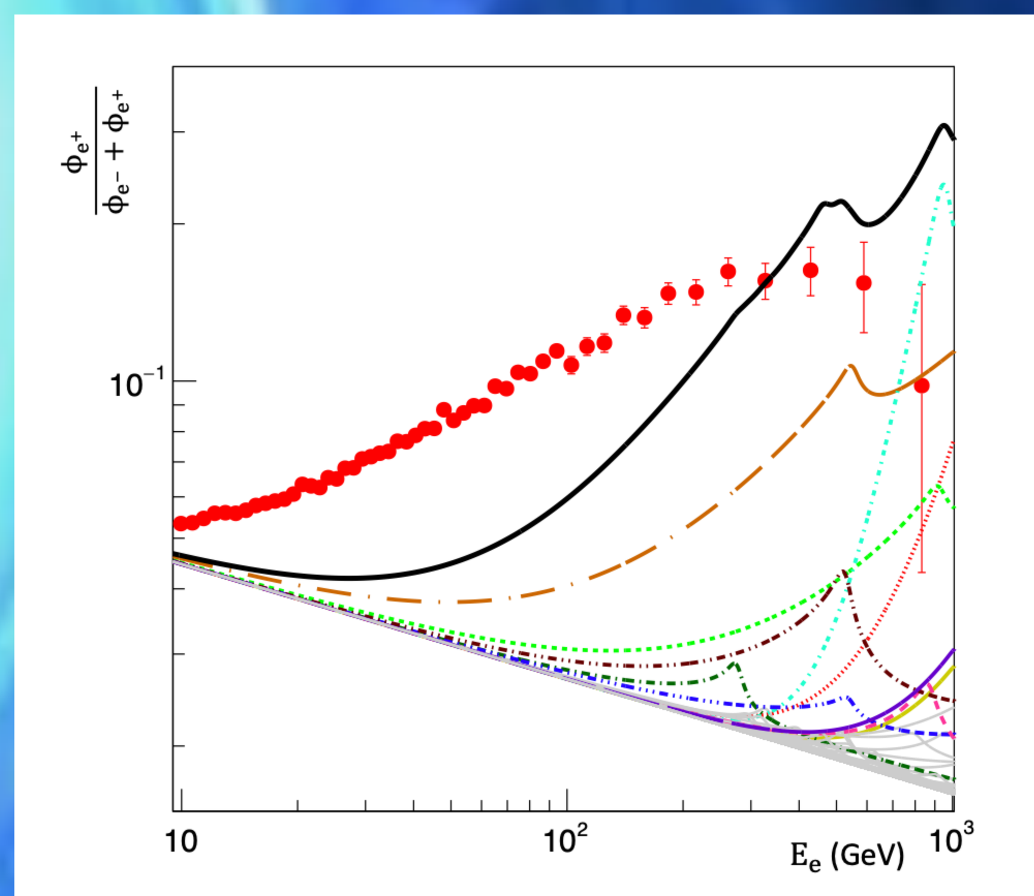

Figure 3: (Above)
Positron fraction calculated for each of the 103 pulsars in the ATNF catalog that are located within 3 kpc of the Solar System and younger than $\tau_c < 10^6$ years (thin colored/shaped lines), and from the sum of all 103 of these sources (top-most/thick black line). For the color key, see Table 1. In this figure, we have adopted the following parameters: α = 1.5, η = 0.15, τ = 10^4 yr, B_{ISM} = 3 μG, and t_{PWN}= 3 × 10^4 yr. For each pulsar, we adopt values of τ_c (characteristic age), distance, and period as reported in the ATNF catalog.

Pulsar Name	P (s)	d (kpc)	τ_c (yr)	Color (Fig. 3)	Line Style (Fig. 3)
J1302-6350	0.048	2.63	3.22×10^5	Light Blue	
J1057-5226	0.197	0.093	5.25×10^5	Orange	
J0117+5914	0.101	1.77	2.65×10^5	Red	
J0633+1746	0.237	0.190	3.32×10^5	Light Green	
J2032+4127	0.143	1.33	1.91×10^5	Violet	
J0908-4913	0.107	1.00	1.02×10^5	Yellow	
J2030+4415	0.227	0.720	5.45×10^5	Brown	
J1846+0919	0.226	1.53	3.50×10^5	Pink	
J1745-3040	0.367	0.200	5.36×10^5	Blue	
J1530-5327	0.279	1.12	9.34×10^5	Green	

Table 1: (Above)
The 10 pulsars contained in the ATNF catalog which contribute the most to the local positron flux. For each pulsar, we provide the reported period (P), distance (d), and characteristic age (τ_c). Also given are the colors/styles assigned to each of these pulsars in Fig. 3.

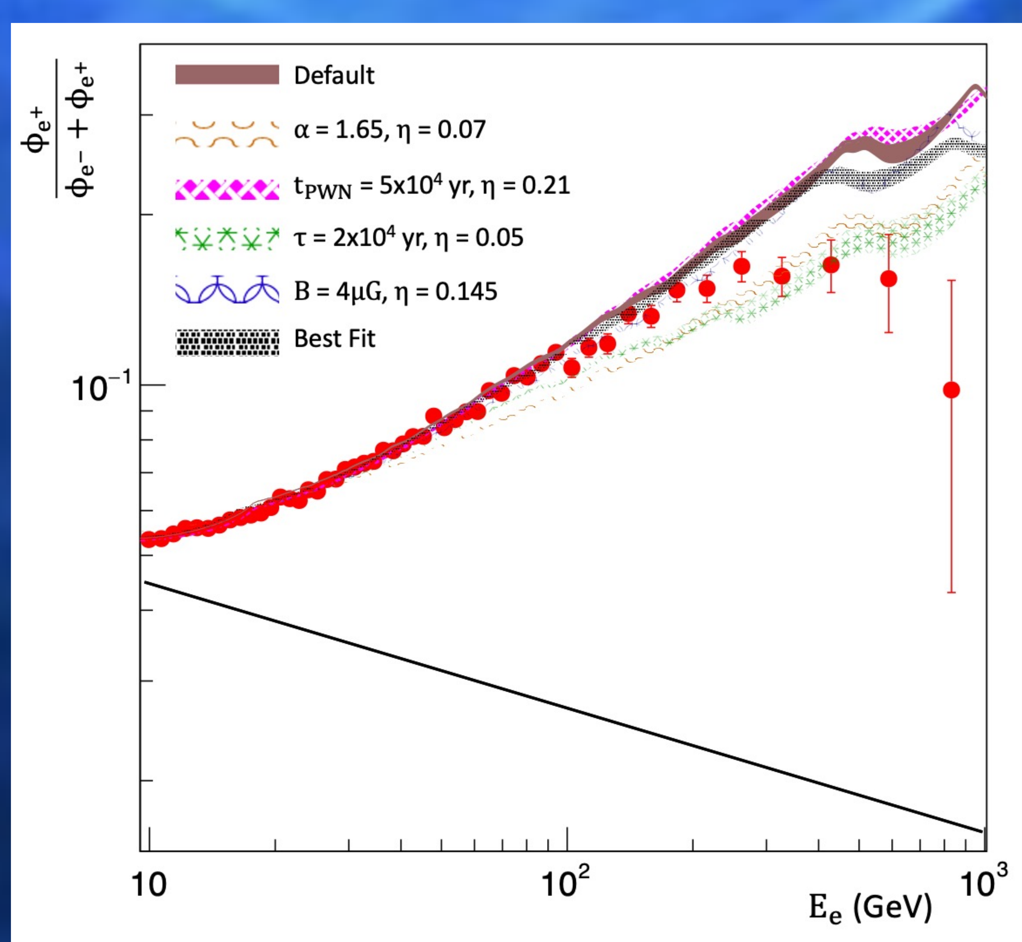

Figure 4: (Right)
Positron fraction sum contributions observed across 68% (all) of the MC realizations. Shown for the initial default case (same parameters as Fig. 2 in solid brown, as well as the best fit for a reasonable choice of parameters when we vary only one of the four main free parameter choices at a time: i.e. spectral index (α) in orange half circles, pulsar injection time (t_{PWN}) in magenta weave, spin-down time (τ) in green stars, and magnetic field (B_{ISM}) in blue braids. Also included is the final best fit when analyzing the variations shown in small black dots for the following main parameters: α = 1.5, η = 0.1, τ = 10^4 yr, B_{ISM} = 4 μG, and t_{PWN} = 5 x 10^4 yr.

Discussion/Conclusion

Pulsar populations do provide a highly likely solution to the positron excess problem as indicated via observations of "TeV Halos" around them. Furthermore, pulsars within 3 kpc of Earth and younger than a million years contribute the most. In varying many free parameters, we have further constrained what pulsar characteristics of both known and unknown pulsar sources must have in order to provide the best fit to AMS data. In particular, the positron fraction at low energies seems to come from many sources, is largely insensitive to age and location, can agrees well with the data for reasonable parameters. However, at high energies, we see that the specific choice of free parameters greatly influences the positron fraction and making it impossible to reliably predict. (this is dominated by only a few sources) This also makes it harder to draw reliable conclusions pertaining to the Milky Way's broader pulsar population.

Acknowledgements

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