Pulsars remain likeliest source of positron excess; cosmic rays traverse pockets of inefficient diffusion

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Key Concepts

- Can nearby pulsars reproduce the anomalous positron excess, under the assumption of inhomogeneous diffusion through pulsar wind nebulae?
- Do the effects of inhomogeneous diffusion extend to galactic scales?
- Can our prediction be verified by studying diffuse gamma ray emission?

Abstract

[1] Measurements of the positron flux anomalously increase with energy above ~10 GeV. The proposed explanations include pulsars, dark matter annihilation, or unknown secondary production mechanisms. Recent TeV observations of pulsars Geminga & Monogem by the HAWC collaboration[2] suggest that high-energy electron and positron diffusion is highly inefficient within their pulsar wind nebulae (PWNe). The HAWC collaboration concluded, under the assumption of homogeneous & isotropic diffusion, that the two pulsars could be ruled out as sources of the anomalous positron flux. Here, we argue that the diffusion coefficient is *not* homogeneous, and solve the governing diffusion equation using a Monte Carlo method. We've found that (i) in the case of Geminga, the positron spectrum at Earth closely matches observations and (ii) the effects of pockets of inefficient diffusion likely extend to Galactic scales. We also discuss how this prediction can be tested using diffuse Galactic gamma ray emission.

Numerical Method

Calculating the cosmic ray flux involves solving an ugly partial differential equation, which gets uglier when assuming inhomogeneous diffusion. The Green's function solution in the case of spherical symmetry and *homogeneous* diffusion is [3]:

$$\psi(t,r,E) = \frac{N(E_o)P(E_o)}{\pi^{3/2}P(E)r_{\text{diff}}^3} e^{-r^2/r_{\text{diff}}^2}$$

Our goal then is to generalize this solution to inhomogeneous diffusion, which we do by employing a Monte Carlo method; we inject a large number of particles at the source, and then evolve the position of the Green's function by allowing the particles to stochastically move at every step via the following prescription:

$$x_{i+1} = x_i + \eta r_{\text{diff}}$$
$$\eta \sim \text{Gaussian variate}$$

When we evolve this distribution of particles, we're evaluating our differential equation within very thin shells, within which the diffusion coefficient is essentially constant, allowing us to circumnavigate the issue of inhomogeneity. In the case of a step-like discontinuity in the diffusion coefficient, the procedure remains valid because at the discontinuity the Monte Carlo method naturally enforces particle number and flux conservation.

An advantage of the Green's function approach is that the loss rate, P(E), and the initial injection spectrum, N(E), have arbitrary energy-dependence. In this work, we assume a power-law injection spectrum and include synchrotron and inverse Compton contributions to the loss rate:

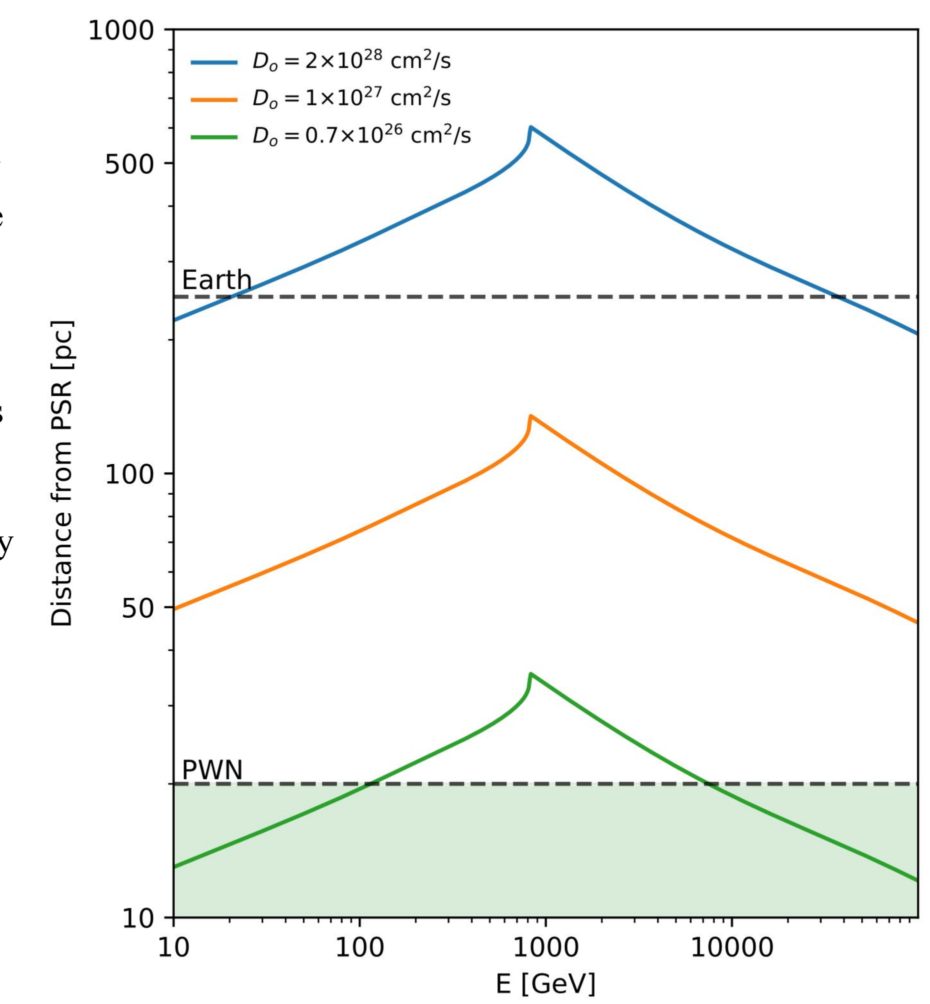
$$P(E) \propto E^2$$
$$N(E) \propto E^{-\alpha}$$

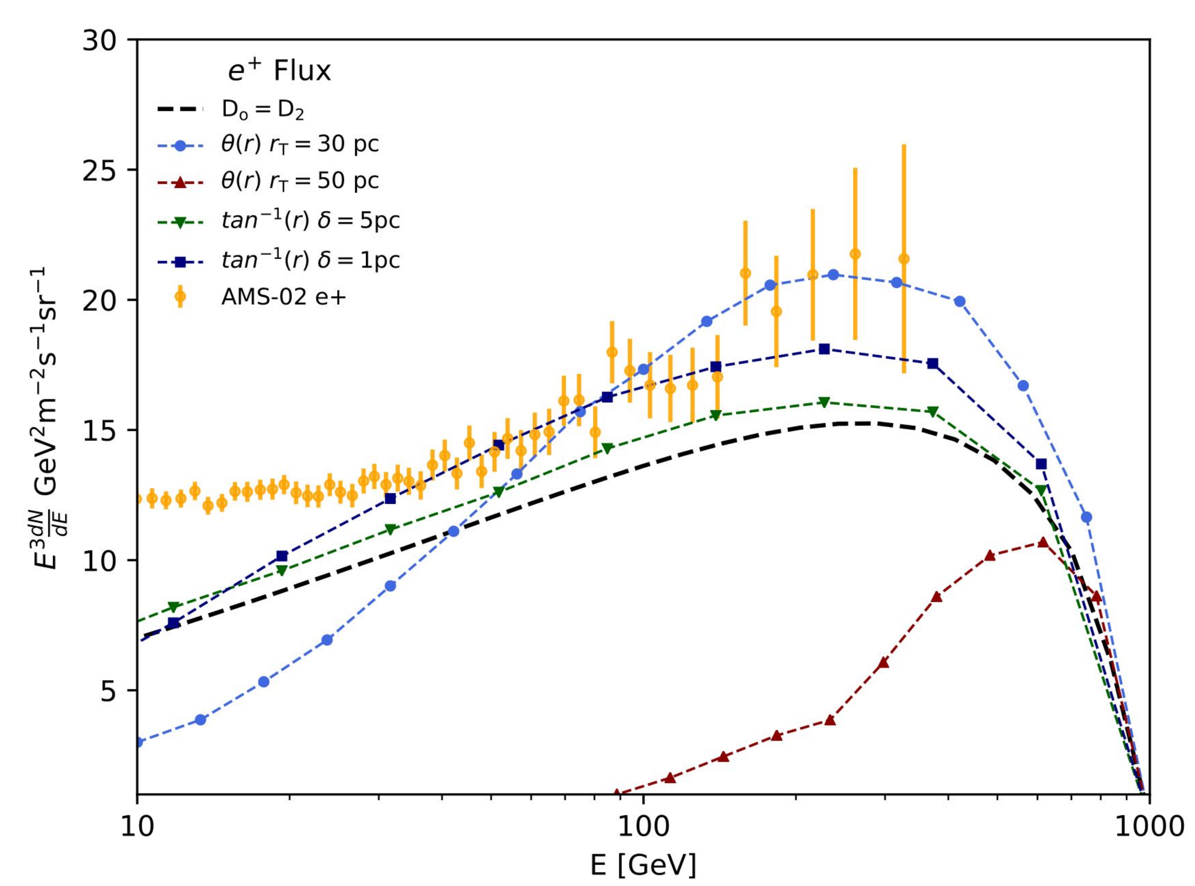
Results

Higher values of the diffusion coefficient allow cosmic rays to travel larger distances. On the right, diffusion lengths are plotted with respect to energy for different values of the diffusion coefficient. In the blue, the Interstellar Medium (ISM) value is plotted, where particles across the energy spectrum easily escape the pulsar wind nebula (PWN). In the green, the PWN value is plotted, indicating energies below 100 GeV and above 10 TeV are trapped within the PWN, while cosmic rays within these bounds will reach Earth more easily. This is important, because this is exactly where we observe the positron excess.

The diffusion length is proportional to the diffusion coefficient and inversely proportional to the energy loss rate, and these competing terms are responsible for the peak at 1000 GeV. Below 1000 GeV, the diffusion length is dominated by the diffusion coefficient, and above 1000 GeV it's dominated by the energy loss rate.

$$r_{\text{diff}}^2 = 4\int_E^{E_o} D(x)/P(x)dx$$
$$D \propto E^{1/3},\ P \propto E^2$$





On the left, we present the fluxes yielded by our Monte Carlo algorithm for multiple arctangent and step-like functional forms of the diffusion coefficient. Values are compared with AMS data, and invariably our results produce a similar excess to the observed flux.

In this case, we used appropriate values for the Geminga pulsar, as follows:

$$t = 342000 \text{ yr}$$
$$r = 250 \text{ pc}$$
$$\alpha = 2.34$$
$$D_{\text{PWN}} = 3.86\times10^{26}\text{cm}^2\text{s}^{-1}$$
$$D_{\text{ISM}} = 3.86\times10^{28}\text{cm}^2\text{s}^{-1}$$

Do the effects of inefficient diffusion extend to galactic scales? We study this by first using estimates for the radial evolution of PWNe and applying it to known, catalogued pulsars. We then used a mesh-based numerical procedure to estimate the total volume of PWNe.

Of course, the sample of known pulsars is incomplete, so we applied correction factors for both the radial distribution of pulsars in the galaxy and for beaming factors due to the relative inclination of the spin and magnetic dipole axes. With incompleteness accounted for, we plotted the total PWN volume as a function of the characteristic age cut off, to the right.

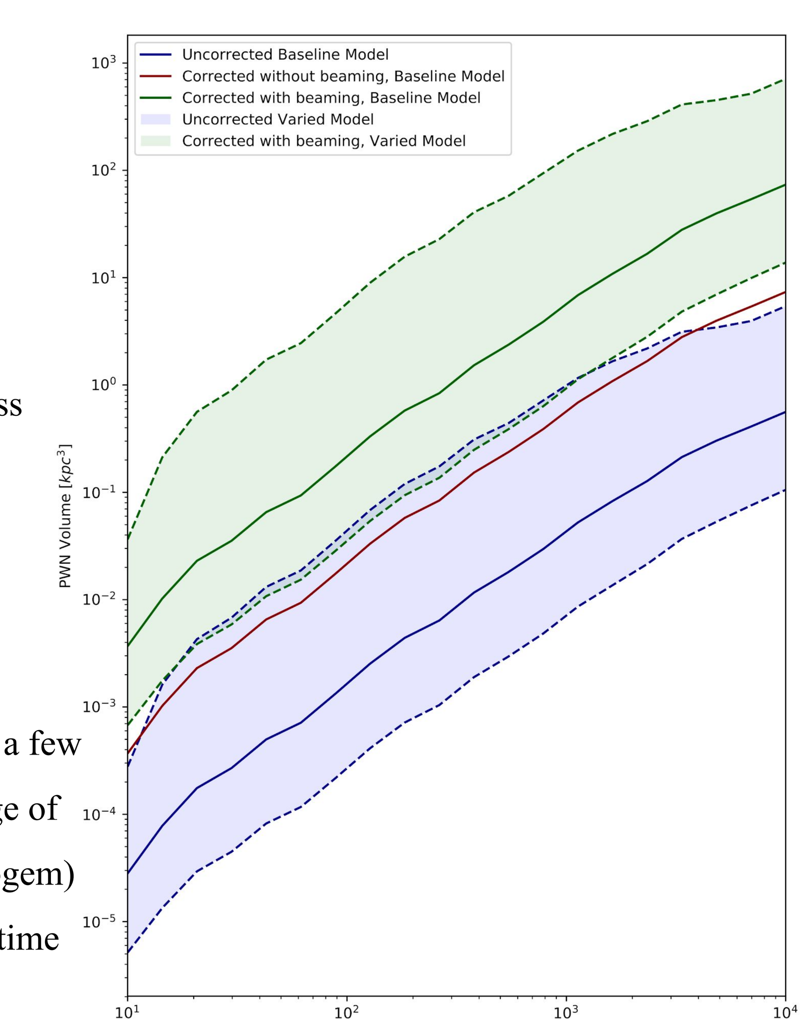
We then want to consider how long cosmic rays spend in pockets of inefficient vs efficient diffusion. We do this by estimating the mean free path (right), and evaluating its proportionalities (below).

$$\langle\lambda_{\text{mfp}}\rangle \sim \sqrt{D\cdot t}$$

(mean free path)

$$\frac{t_{\text{PWN}}}{t_{\text{ISM}}} \sim \left(\frac{\langle V\rangle_{\text{PWN}}}{\langle V\rangle_{\text{ISM}}}\right)^{2/3} \frac{D_{\text{ISM}}}{D_{\text{PWN}}}$$

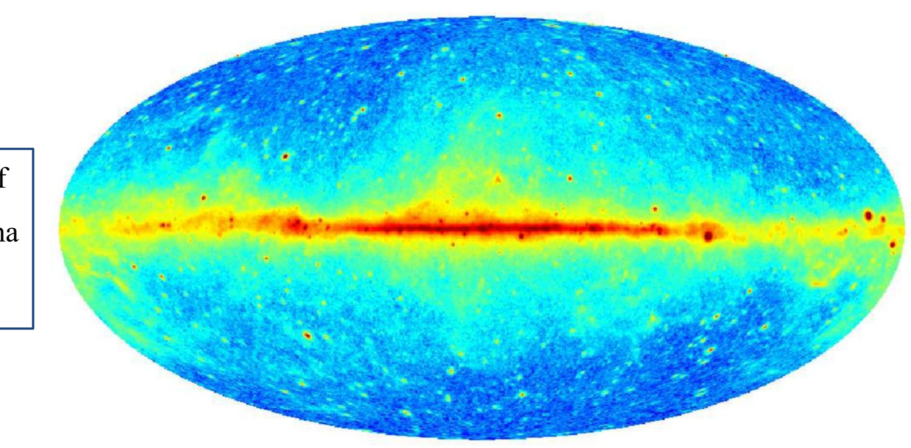
For characteristic age cut off of a few million years or greater (near the age of the TeV halos of Geminga & Monogem) cosmic rays end up spending *more* time in regions of inefficient diffusion!

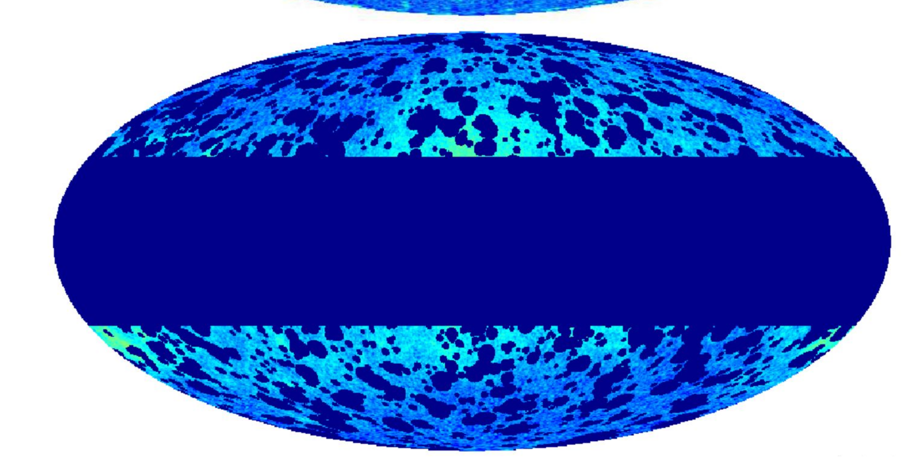


Current Efforts

Our present focus involves the development of code that expands upon our numerical method. Results in this presentation are given for an individual pulsar in the case of delta-like emission. We're currently modeling continuous emission, corresponding to the spin-down luminosity of a given pulsar, for multiple sources. From this, we obtain a more accurate measure of the positron flux at Earth, and by integrating the column densities of our particles we can simulate a map of diffuse gamma ray emission. The goal is to then take this simulated data, compare it to observations of the diffuse gamma ray sky (example from the *Fermi* Large Area Telescope below), and to construct matching angular power spectra.

Fermi map of all-sky gamma ray emission.





We want this image, except inverted!

[4] Fornasa et. al. 2016

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References

[1] S. Profumo et. al. "Lessons from HAWC PWNe observations: the diffusion…" (2018)

[2] A. U. Abeysekara et al. (HAWC), Science **358**, 911 (2017), 1711.06223

[3] A. M. Atoyan, F. A. Aharonian, and H. J. V ̈olk, Phys. Rev. D **52**, 3265 (1995)

[4] M. Fornasa et al., Phys. Rev. **D94**, 123005 (2016), 1608.07289.