Updated Constraints on Pulsar Explanations for Positron Excess

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Since the early 2000s, many cosmic ray telescopes and modules such as AMS-01, HEAT, and PAMELA have all indicated a substantial deviation in the observed **positron fraction** compared to the standard predictions of secondary productions of cosmic rays.

- **positron fraction or flux ratio:** the ratio of the number of positrons to the combined number of electrons plus positrons present in the interstellar medium (ISM) - space between the astronomical bodies.

- These observations were *first* seen at energies roughly between 1 - 100 GeV.

- More recently, data from AMS-02 has shown that this tension is more noticeable up to at least 1 TeV.
Goals to answer:

What source could explain this tension?
And under what constraints can the contribution provide the best fit?
One plausible solution to solve this ongoing tension is to consider pulsars - spinning neutron stars that are magnetized.

Pulsars are a great source of high energy positrons and electrons because:

- Relatively young and nearby pulsars have high gamma ray emissions as seen in experiments such as HAWC (High Altitude Water Cherenkov).
- The gamma ray emission is produced by high energy particles such as positrons that are injected from pulsars into the interstellar medium.
More specifically, the high energy positrons that are injected into the ISM from pulsars, emit gamma rays through inverse Compton scattering and synchrotron radiation.

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 equation).
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\[
\frac{\partial}{\partial t} \frac{dn_e}{dE_e}(E_e, r, t) = \nabla \cdot \left[ D(E_e) \nabla \frac{dn_e}{dE_e}(E_e, r, t) - \nu_e \frac{dn_e}{dE_e}(E_e, r, t) \right] \\
+ \frac{\partial}{\partial E_e} \left[ \frac{dE_e}{dt} \frac{dn_e}{dE_e}(E_e, r, t) \right] + \delta(r)Q(E_e, t)
\]

- $r = $ Distance from our galactic center
- $E_e = $ electron/positron energy
- $t = $ cosmic time since pulsar birth

Propagation equation
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Positron number density

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$$+ \frac{\partial}{\partial E_e} \left[ \frac{dE_e}{dt} \frac{dn_e}{dE_e}(E_e, r, t) \right] - \delta(r) Q(E_e, t)$$
The differential number density term from the previous equation is most useful to describe the distribution of a single pulsar source. 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. One can extract the pulsar contribution to the positron flux ratio for many free parameters.

\[
\frac{dn_e}{dE_e}(E_e, r, t) = \frac{Q_0 E^{2-\alpha}}{8\pi^{3/2} E_e^2 L_{\text{dif}}^3(E_e, t)} \exp\left[-\frac{E_0}{E_c}\right] \exp\left[-\frac{r^2}{4L_{\text{dif}}^2(E_e, t)}\right]
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Answer: include pulsar contributions to ISM predictions

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The following results and analysis builds upon previous work done by Hooper, Linden, and collaborators*.

They already proposed that young and nearby (to Earth) pulsars could best explain the positron excess.

These are updates to further constrain what characteristics pulsars should have in order to contribute the most to the positron flux excess.

INCLUDING THE PULSAR CONTRIBUTION...

Contribution from only the Geminga pulsar in green (it is both nearby and young).

Note: The above contribution used a specific set of free parameters: an efficiency of 29%, a spectral index of 1.9 and a spectral energy of 50 TeV.
The free parameters which constitute the characteristics exhibited by pulsars within a given population. The main ones that affect the pulsar flux contributions are:

- **Spin-down Time**: time between injections of particles into the ISM.

- **Spin-down Flux**: rate of rotational kinetic energy lose per distance from Earth squared – this is used as a threshold for determining MC sources already detected by gamma rays.

- **Efficiency**: percent of rotational kinetic energy loss from injection.

- **Spectral Index**: indicator of particle flux density in the power-law distribution concerning frequencies of positrons and electrons.

- **Pulsar Birth Rate**: rate per century of the number of pulsars born.

- **$F_{\text{beam Radio}}$ and $F_{\text{beam Gamma}}$**: fractions of MC sources that are considered to be detected (either by gamma rays or in radio) and catalogued in ATNF.
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Preliminary analysis has further constrained that:

- **Pulsars younger** than a million years and **within 3 kpc of Earth** to contribute the most.*

- But pulsars between a million years to ten million years old are still included as they raise the ISM prediction threshold. (orange dashed line)

- Also, included are all **known** pulsar sources **younger** than a million years and **within 3 kpc of Earth**. (blue dashed line).

- And, the Monte Carlo simulations that cover sources **not yet known**. (purple dashed line)

- Note that for each energy bin, the three dashed lines on the right add up to the solid green line.

*Note that the three dashed lines **exclude** pulsar sources further than 3 kpc away from Earth. Our analysis showed that they contribute negligibly.
Best fit so far…

- An example contribution showing how the three considerations add to give a total pulsar contribution to the flux ratio.

- Free parameters:
  - spin-down time of $1 \times 10^4$ years
  - spin-down flux of $5 \times 10^{42}$ ergs/kpc$^2$/yr
  - efficiency of 1.8%
  - spectral index of 1.9
  - pulsar birth rate of 1 per century
  - $F_{\text{beam}}$ radio of 15% and $F_{\text{beam}}$ gamma of 50%

- Past 100 GeV, the deviation indicates that further adjusting of parameters is needed to provide a better fit.

- One should note that this result is a “simple case” where it assumes that all MC generated pulsars have the same spin-down time and period which, in reality, would not be the case.
Another look at the same conclusion statistically...

- The histogram shows the distribution of the gamma ray sources in ATNF broken up by distance range.
- The line plots that are overlaid are the average values of 10 MC source distributions that follow the same parameters as shown in the plot on the previous slide.
The table lists the Poisson probability or likelihood of the “focus” parameters (spin-down time and spin-down flux) to show quantitatively which set is more favored to explain the positron excess.

<table>
<thead>
<tr>
<th>Spin-down Flux</th>
<th>5 x 10^3 years</th>
<th>1 x 10^4 years</th>
<th>2 x 10^4 years</th>
<th>5 x 10^4 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 10^{42} ergs/kpc^2/yr</td>
<td>6.63 x 10^{-27}</td>
<td>4.74 x 10^{-33}</td>
<td>8.77 x 10^{-56}</td>
<td>3.91 x 10^{-97}</td>
</tr>
<tr>
<td>5 x 10^{42} ergs/kpc^2/yr</td>
<td>1.15 x 10^{-36}</td>
<td>7.17 x 10^{-30}</td>
<td>1.96 x 10^{-58}</td>
<td></td>
</tr>
<tr>
<td>1 x 10^{43} ergs/kpc^2/yr</td>
<td>5.57 x 10^{-44}</td>
<td>9.63 x 10^{-30}</td>
<td>1.72 x 10^{-28}</td>
<td>8.12 x 10^{-48}</td>
</tr>
<tr>
<td>5 x 10^{43} ergs/kpc^2/yr</td>
<td>4.37 x 10^{-50}</td>
<td>1.44 x 10^{-43}</td>
<td>8.49 x 10^{-35}</td>
<td>8.29 x 10^{-28}</td>
</tr>
</tbody>
</table>

Best likelihood so far for the given combination of parameters. There is agreement on what these parameters should be from both numerical and graphical analysis.
CONCLUSIONS

- Pulsar populations do provide a **very plausible solution** to the positron excess problem.
- Furthermore, sources **within 3 kpc** of Earth and **younger than a million years old** contribute the most.
- In the preliminary results, a **simple case** of fixing most free parameters – the only two that change being **the spin-down time and spin-down flux**.
  - With these assumptions, the full contribution from all three considerations add to provide a **very good fit to AMS data**.

- Further work will seek to constrain the free parameters **more precisely**.
- **Final results soon be published.**
THANK YOU!
BACK UP SLIDES
Process of obtaining pulsar contribution:

Geminga differential number density

Time profiles: shows the differential number density after every 10,000 years. One adds the profile's value per energy bin to obtain the black line at the top of the plot.

For each energy bin: Take *half* of the black line and add it to the ISM positron contribution and also to the ISM electron contribution.

\[ Q(E, t) = \delta(t) Q_0 E^{-\lambda} \exp\left(-\frac{E}{E_c}\right) \]
Process of obtaining pulsar contribution:

The Geminga contribution is the “halved” amount plotted in the previous slide.

The positron fraction is the flux ratio.

\[
\text{Positron fraction} = \frac{\text{ISM positron} + \text{Geminga contributions}}{(\text{ISM positron} + \text{Geminga}) + (\text{ISM electron} + \text{Geminga}) \text{ contributions}}
\]
Process of obtaining Poisson probability:

Probability or Likelihood = \[ \prod \frac{\lambda(i)^k(i) e^{-\lambda(i)}}{k(i)!} \]

Histogram: ATNF \((k(i))\)
Scatter Plots: Average of 10 MCs \((\lambda(i))\)

Note that this is done for each distance consideration, not just per energy bin. Hence, the index goes up to 60 terms.
Pulsar ages and their characteristics:
(a sample MC of pulsars from $10^5$ years to $10^6$ years)

This reasoning is the same for known ATNF sources.

Age differences cause the extra “humps” in contributions. – impacts at what energy the pulsar can provide a substantial contribution.

After about $\sim 3 \times 10^5$ years, the sources drop off at higher energies.
Pulsar ages and their characteristics:
(a sample MC of pulsars from $10^5$ years to $10^6$ years)

Example: Monogem versus Geminga (+ one million to ten million threshold MC sources) with a spin-down time of $10^4$ years. The spectral indices range from 1.8 to 2.2. The pulsar birth rate is 0.673 per century.

For a low spectral index (alpha), one can see that Monogem’s age compared to Geminga’s age produces two “humps” in the contribution.

Monogem age: $1.1 \times 10^5$ years old
Geminga age: $3.7 \times 10^5$ years old

Note that the saw-tooth effect here is due to lower statistics in combination with the chosen parameters.