Qeios

Peer Review

Review of: "Slow diffusion around pulsar γ-ray halos and its impact on cosmic rays propagation"

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From my reviewer's perspective, this article addresses a relevant and timely topic in high-energy astrophysics, namely the role of suppressed diffusion around pulsars and its consequences for γ-ray halos, cosmic-ray propagation, and the positron excess. The manuscript presents a coherent argument that the ballistic-diffusive scenario with a conventional fast diffusion coefficient does not provide an equally satisfactory description of the observed γ-ray surface-brightness profiles, while also requiring energetically unfavorable conversion efficiencies, thereby supporting the slow-diffusion interpretation. The discussion of the two-zone diffusion model and its implications for nearby pulsar contributions to the AMS-02 positron spectrum is particularly interesting. However, the manuscript would benefit from a clearer distinction between results obtained directly in the present work and results previously published in the cited references, as a substantial part of the discussion summarizes earlier studies. In addition, the presentation would be strengthened by providing more explicit information on the underlying transport models, fitting procedures, and assumptions, particularly when extending the argument from individual slow-diffusion regions to an effective slow-diffusion Galactic disk. The conclusions regarding the viability of dark matter interpretations should also be presented with appropriate emphasis on their dependence on the adopted propagation model. Overall, the article provides a valuable synthesis of several related results and addresses an important problem in cosmic-ray physics; however, improvements in methodological clarity, discussion of model dependence, and language would strengthen the manuscript.

The central question is whether the γ-ray halos observed around pulsars such as **Geminga, Monogem, and PSR J0622+3749** require a region of **strongly suppressed diffusion**.

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The article argues that: **Slow diffusion around pulsars is necessary to reproduce the observed γ-ray halo profiles.** It then investigates how these slow-diffusion regions affect:

1. The propagation of electrons and positrons from nearby pulsars.
2. The origin of the positron excess measured by AMS-02.
3. Galactic cosmic-ray propagation through a possible **slow-diffusion disk**.
4. Dark-matter annihilation models for the positron excess.

The article is organized in a logical progression:

Introduces the discovery of extended γ-ray halos and the evidence for a diffusion coefficient around pulsars that is much smaller than the standard interstellar-medium value. It presents the two-zone diffusion model as a way to reconcile local slow diffusion with standard Galactic cosmic-ray propagation.

Tests whether a **ballistic-diffusive (BD) propagation model** can explain γ-ray halos without invoking slow diffusion.

The conclusion is that it cannot adequately reproduce the surface-brightness profiles and requires unrealistically high energy-conversion efficiencies.

Examines whether nearby pulsars can explain the AMS-02 positron excess under the two-zone diffusion model.

The article identifies **B1055-52** as a potentially favorable source because of its age and possible proximity.

Extends the idea from individual pulsars to the Galactic disk. If many pulsars are surrounded by slow-diffusion regions, their cumulative effect could lead to slower average diffusion in the Galactic disk.

The article argues that this modified propagation model can make dark-matter explanations of the positron excess compatible with γ-ray constraints. Summarizes the three main conclusions: slow diffusion is necessary for γ-ray halos, nearby pulsars can contribute significantly to the positron excess, and a slow-diffusion disk can reopen viable dark-matter parameter space.

The standard diffusion equation is non-relativistic and, under some circumstances, can imply propagation faster than the speed of light for recently injected particles.

The ballistic-diffusive model attempts to correct this by assuming:

- initially **ballistic propagation**,
- followed by **diffusive propagation** after particles travel beyond the magnetic-field coherence scale.

The authors compare this model with observations of Geminga and LHAASO J0621+3755.

Their conclusion is important:

- A fast-diffusion BD model produces profiles that are too broad after convolution with the detector point-spread function.
- The fits are significantly worse than those obtained using slow diffusion.
- The required conversion of pulsar spin-down energy into high-energy electrons and positrons can exceed physically reasonable values.

Thus, the article concludes that the BD mechanism does **not eliminate the need for slow diffusion**.

This is arguably the **strongest and most central result of the article**.

A major conceptual strength of the paper is the two-zone model.

The physical picture is:

Pulsar→slow-diffusion region→normal interstellar diffusion\text{Pulsar} \rightarrow \text{slow-diffusion region} \rightarrow \text{normal interstellar diffusion}

The slow-diffusion region has a finite radius r∗r_*. Outside this region, the diffusion coefficient returns to the conventional Galactic value.

This is important because assuming slow diffusion everywhere in the Galaxy would strongly affect secondary cosmic-ray observables such as B, Li, Be, antiprotons, and diffuse γ rays. The localized two-zone model avoids this problem.

The article revisits the well-known positron excess observed by AMS-02.

A difficulty arises because, if diffusion remains slow everywhere between Geminga and Earth, high-energy positrons have difficulty reaching Earth.

The two-zone model changes this situation:

- particles are initially confined near the pulsar,
- then escape into the standard diffusion region,
- allowing certain nearby and sufficiently old pulsars to contribute significantly.

The article highlights **B1055-52** as an ideal candidate under the assumed distance. However, the author appropriately notes that the distance remains uncertain and that the broader conclusion does not depend exclusively on this particular pulsar.

This is probably the most speculative but also one of the most interesting parts of the article.

The argument is:

- middle-aged and old pulsars may commonly possess slow-diffusion halos;
- the Milky Way may contain approximately 10410^4 such regions;
- if these regions occupy a significant fraction of the Galactic disk, the effective diffusion in the disk could be slower than outside the disk.

This is an interesting hypothesis, but it deserves stronger discussion of the **transition from localized slow-diffusion bubbles to an effective macroscopic Galactic diffusion coefficient**.

This is one of the main conceptual points where the paper could be strengthened.

The article argues that in the slow-disk model:

The article states that the preferred parameter region becomes compatible with the γ-ray and CMB constraints considered in the analysis.

Scientifically, this conclusion is interesting, but it should be interpreted carefully because dark-matter constraints and propagation models are strongly model-dependent.

The article addresses a well-defined physical problem: Can γ-ray halos around pulsars be explained without strongly suppressed diffusion?

The answer developed through the analysis is clear and consistent.

The article successfully connects:

- particle transport near individual pulsars,
- γ-ray halo observations,
- local cosmic-ray measurements,
- Galactic propagation,
- positron excess,
- dark matter.

This gives the work a broad scientific scope.

The discussion is anchored in observations from HAWC, LHAASO, and AMS-02 rather than being purely theoretical.

The use of the required pulsar energy-conversion efficiency as an additional criterion is particularly valuable.

A model should not merely fit the profile statistically; it should also satisfy the available energy budget. The article uses both criteria.

For a physics audience, particularly graduate students or researchers entering the field, the article would benefit from explicitly presenting the fundamental transport equation. The article discusses diffusion coefficients and propagation models extensively but provides relatively little mathematical derivation.

The article itself acknowledges uncertainty in the distance of B1055-52. This is important because the predicted positron contribution is highly sensitive to distance.

The article correctly notes that the broader parameter-space argument is more robust than the identification of one specific pulsar. However, the presentation could make this distinction clearer. The article is generally understandable, but the English could be improved substantially in places.

Examples of issues include:

- “the curves do show two minimal” → **the curves show two minima**
- “can not” → **cannot**
- “the cosmic rays anisotropy” → **cosmic-ray anisotropy**
- “an ideal source for the positron excess” could be softened to **a promising candidate source**
- some sentences are repetitive, particularly when introducing results already discussed in cited references.

The style would benefit from:

1. Shorter sentences.
2. More precise terminology.
3. Reduced repetition.
4. Clearer distinction between **results obtained in this article** and **results reproduced from previous publications**.

Declarations

Potential competing interests: No potential competing interests to declare.