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Particle Transport in Pulsar Halos and Their Contribution to the Diffuse Galactic Gamma-ray Emission

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In this contribution, we discuss the particle transport mechanism in pulsar halos. The isotropic diffusion model requires a feasible way of generating strong turbulence in the ambient interstellar medium. The streaming instability driven by escaping electron/positron pairs is not sufficient, but it might work with certain pre-amplification of the turbulence. The anisotropic diffusion model predicts many pulsar halos with elongated morphology, which are currently not detected. We demonstrate that those elongated halos are difficult for detection, but long-term exposure of LHAASO may discover some of them, which may serve as a critical test of the model. Finally, we show that pulsar halos, with either model, may have important contribution to the diffuse Galactic gamma-ray emission (DGE).

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1. INTRODUCTION

Pulsar halos are a new class of very-high-energy (VHE) gamma-ray sources identified recently around a few middle-aged pulsars, i.e., the Geminga pulsar, the Monogem pulsar, and PSR J0622+3749 [1, 2]. These sources are spatially extended and are believed to be generated by inverse Compton radiation of electron/positron pairs that escape from pulsar wind nebulae (PWN) [3–5], and the detection of gamma-ray radiation above a few tens of TeV indicates acceleration of ~ 100 TeV pairs escaping from the PWNe. The measured 1D TeV gamma-ray surface brightness profiles (SBP) of pulsar halos all show a steep decline with the angular distance from the pulsar's position, supporting the picture that the gamma-ray emission is powered by the pulsar.

An important implication from the SBP is the slow diffusion of electron/positron pairs in the halos. Take the halo around the Geminga pulsar for instance, the measured SBP indicates a significant decrease of the pair density at $\sim 10\,$pc from the pulsar. For a typical interstellar magnetic field of 3μG and the radiation field, the cooling timescale of 100 TeV electrons/positrons is generally $t_{\rm cool} \sim 10\,$kyr. Thus, the typical diffusion length of these pairs, i.e., $2\sqrt{Dt_{\rm cool}}$, should be comparable to 10 pc, leading to $D(100\,{\rm TeV}) \lesssim 10^{28}{\rm cm}^2/{\rm s}$. This diffusion coefficient is significantly lower than the standard diffusion coefficient in the ISM, as inferred from the measurement of the primary-to-secondary cosmic-ray flux ratio.

Note that the diffusion coefficient depends on the cooling timescale. In principle, such an extremely small diffusion coefficient may be avoided if pairs cool more efficiently in the ISM. This may be achieved in the presence of a stronger interstellar magnetic field around these pulsars. On the other hand, 100 TeV pairs will radiate keV photons via the synchrotron radiation in the magnetic field, so the X-ray observations may shed some lights on the magnetic field. Liu et al. [6] analyzed the data of Chandra and XMM-Newton around the Geminga pulsar. It is found that the X-ray SBP around the pulsar is flat, suggesting the X-ray emission is dominated by the background in that region. This results in a stringent upper limit of the synchrotron flux of the pulsar halo and subsequently suggests the interstellar magnetic field around the pulsar to be weaker than $0.8\,\mu$G. The weak magnetic field requires an even smaller diffusion coefficient to explain the measured TeV SBP. On the other hand, one may assume a spatially dependent diffusion coefficient with increasing value with the radius from the pulsar to help reproduce the gradient in the resulting SBP. The generation mechanism of such a kind of diffusion coefficient is not clear. The rest of this contribution will focus on the particle transport model of pulsar halos and discuss the implication of their emission.

2. The Particle Transport Mechanism in Pulsar Halos

Given the steep decline of the SBP and quasi-spherical morphology of the halo, it is straightforward to consider an isotropic diffusion model with a suppressed particle diffusion around the pulsar, close to the Bohm diffusion limit [7, 8]. The key issue of this model is how to generate the slow diffusion. In general, a suppressed diffusion implies a strong turbulence at the gyroscale of particles. The gyroradius of radiating pairs is $r_L = 0.1(E_e/100{\rm TeV})(B/1\mu{\rm G})^{-1}$, which is much smaller than the injection scale of the external turbulence in the ISM, say, $\sim 10-100\,$pc. Therefore, even the turbulent magnetic field is saturated at the injection scale, the energy density of the turbulence at the gyro-scale of the radiating pairs is much smaller than that of the regular component. One of the

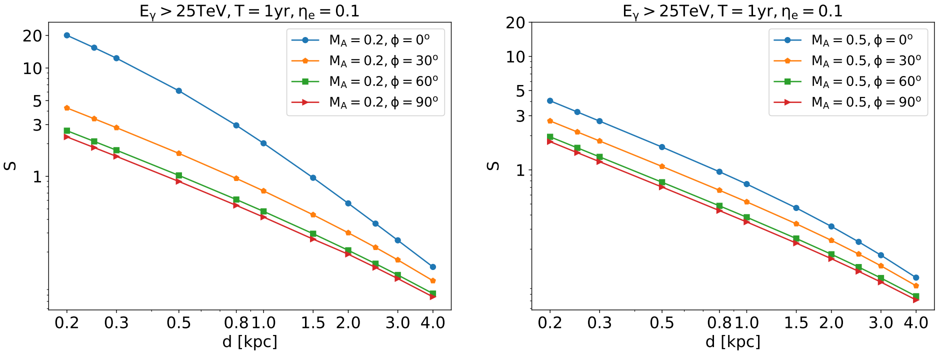

Figure 1: Signal to noise ratio of a Geminga-like pulsar halo as a function of the pulsar's distance, predicted with one year of operation of LHAASO. The left and the right panels show the case of $M_A = 0.2$ and 0.5 respectively. Curves of different colors represent different inclination angles. It is clear that halo of a larger inclination angle is more difficult to be detected. The figure is taken from Ref. [12].

mostly considered turbulence generation mechanism is the streaming instability. In this mechanism, Alfvénic waves in the ISM can be amplified at the gyroscale of pairs in the presence of the pair density gradient. Previous studies Evoli et al. [9], Mukhopadhyay and Linden [10] show that the pair diffusion up to 10 TeV can be suppressed to the required level in a 1D flux tube with a transverse radius of $0.1 - 10$ pc. However, as also pointed out by Ref.[11], the self-regulation at ~ 100 TeV is not significant because the pair energy rate from middle-aged pulsars is not sufficient at such high energies to maintain the turbulence. Some other possible processes driving the turbulence include the shock of related supernova remnant and streaming instability driven by protons accelerated in the shock. Even if these processes alone cannot suppress the diffusion coefficient down to the required level, they may serve as a pre-amplification and facilitate the turbulence generation by pairs.

An alternative model for the pulsar halo is the anisotropic diffusion model [13]. If the interstellar magnetic field is not purely chaotic and has a mean direction, particles will diffuse more rapidly along the mean field direction than perpendicular to the mean field direction, by a factor of M_A^{-4} with M_A being the ratio of turbulent magnetic field to the regular magnetic field. In this case, if the mean magnetic field direction is approximately aligned with the line of sight of the observer towards the pulsar, the projection of the halo would appear a quasi-spherical morphology in the plane of the sky and the apparent size is dominated by the perpendicular diffusion. For $M_A = 0.2 - 0.3$, the perpendicular diffusion coefficient can be suppressed by 2-3 orders of magnitude with respect the parallel one, whereas the latter represent the standard diffusion coefficient inferred from the cosmic-ray measurements. A very weak magnetic field may be also avoided in this case because pairs radiating towards the observer will have a very small pitch angle to the mean magnetic field direction, which suppress the synchrotron radiation efficiency. However, it should be noted that the halo morphology in this model highly depends on the inclination angle between the mean magnetic field in the ambient interstellar medium and the line of sight of observers. If each middle-aged pulsar can generate a halo around it, we can only expect only a small fraction of these halos to possess an aligned mean magnetic field direction with the observer's line of sight. With a larger

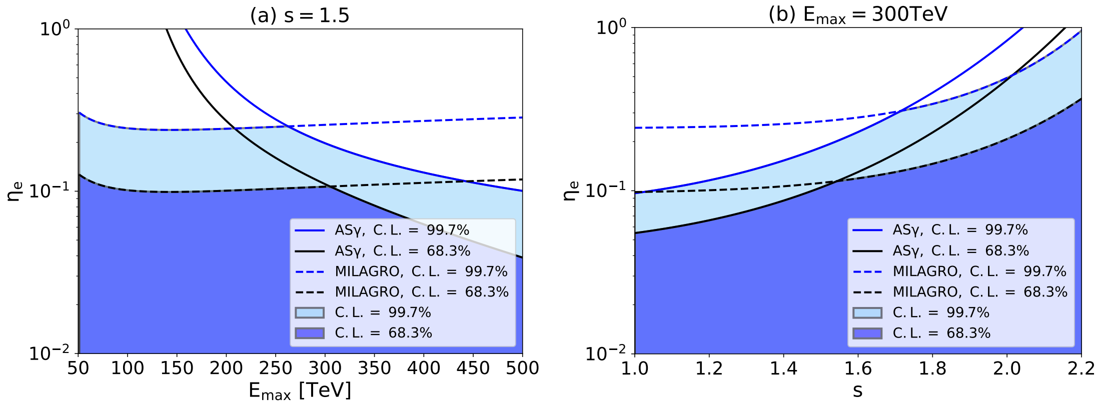

Figure 2: Left panel: Two-dimensional constraints between the maximum pair energy $E_{\rm max}$ and the pair conversion efficiency η_e , with the injection power-law slope s fixed to 1.5, based on the DGE measured by AS$_\gamma$ and MILAGRO; Right panel: two-dimensional constraints between s and η_e, with $E_{\rm max}$ fixed to 300 TeV. Black and blue curves show the boundary of injection parameters that reach 68.3% confidence level and 99.7% confidence level of the measured flux, respectively. Solid and dashed curves represent constraints from AS$_\gamma$ and MILAGRO, respectively. The figure is taken from Ref. [16].

inclination angle, the halo would appear elongated. However, such a kind of pulsar halo has not been observed. Ref.[12] pointed out that it is more difficult to detect a more elongated halo, because they appear more diffuse and will reduce the signal to noise ratio of the detection (see Fig. 1). Therefore, it is reasonable that the first detected three pulsar halos show more or less spherical morphology. On the other hand, sensitive gamma-ray instruments, such as LHAASO, are able to identify those elongated halos with a few year's exposure. Whether such elongated halos can be detected in the near future will be a crucial test to the model.

3. Possible Contribution to the DGE by Pulsar Halos

Pulsars are born from Type II supernova explosion. If each middle-aged pulsars with age less than 1 Myr can power a halo, we would expect ten thousands pulsar halo in the Galaxy given the Type II SN rate in the Galaxy to be $\sim 0.01/\mathrm{yr}$. Obviously, most of these pulsar halos are not detected and hence their emission will contribute to the DGE. Ref.[14] suggested that the collective emission of pulsar halos may be more important than the π^0 emission from interactions between cosmic-ray hadrons and ISM, and dominate the DGE excess measured by MILAGRO. Ref.[15] found that pulsar halos may also have a non-negligible contribution to the DGE measured by Fermi-LAT at $\sim$ 100 GeV band. On the other hand, the measured DGE flux can be regarded as an upper limit for the total flux from pulsar halos, and some model parameters such as the injection spectral index of the pairs and the pair conversion efficinecy (i.e., the fraction of pulsar's spindown power being converted to the energy of pairs) can be obtained based on the DGE measured by AS$_\gamma$ and MILAGRO [16] (see Fig. 2).

Recently, LHAASO reported the measurement of the DGE between 10 – 1000 TeV with a careful subtraction of the source emission. We can compare the DGE flux measured by LHAASO and the IceCube's latest result on the high-energy Galactic neutrino flux after rescaling the flux to the same region of LHAASO's DGE analysis. By doing this, we found that the DGE measured by LHAASO contains a component of leptonic origin, and demonstrated that pulsar halos, with either particle transport model, can be promising sources of this leptonic component [17].

4. Conclusions

In this contribution, we discussed the particle transport mechanisms of pulsar halo. In the isotropic diffusion model, it is important to figure out the generation mechanism of the strong turbulence at gyroscale of emitting pairs. In the anisotropic diffusion model, there are many elongated pulsar halos expected in the Galaxy and identification of these elongated halos would serve as a critical test of the model. With either particle transport model, pulsar halos can be promising contributors to the TeV DGE.

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