PROCEEDINGS OF SCIENCE

Possible origin of the Geminga slow-diffusion halo

Kun Fang^{*1}, **Xiao-Jun Bi**^{1,2} **and Peng-Fei Yin**^{1}

[1] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*
E-mail: `fangkun@ihep.ac.cn`

HAWC measured the angular profile of the TeV γ-ray halo around Geminga, which indicates an anomalously slow diffusion for the cosmic electrons and positrons (electrons hereafter) in this halo region. The origin of the slow-diffusion region is a fresh and intriguing problem. We first check the self-confined scenario, that is, the electrons released by Geminga induce Alfvén waves through streaming instability, and they are then trapped by the Alfvén waves. Considering the proper motion of Geminga pulsar, however, we find that Geminga cannot provide enough electrons in the late age to account for the so slow diffusion. Then we propose another scenario in which the slow-diffusion region is preexisting. Geminga may still be inside the turbulent region left by its parent SNR. The SNR injects energy to the magnetic field turbulence of the background medium, which can be adequate to explain the observed slow diffusion. Some other TeV halos could also be understood under this scenario.

36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

---

[*] Speaker.

PoS(ICRC2019)670

1. Introduction

In late 2017, HAWC collaboration reported the spatially resolved observation of the γ-ray halo around Geminga pulsar [1]. As these very-high-energy (VHE) γ rays are emitted by electrons and positrons[1] mainly through inverse Compton scattering of the cosmic microwave background photons, the surface brightness profile of the γ-ray emission can be a good indicator for the propagation of the electrons near the source. However, the derived diffusion coefficient of the electrons is hundreds times smaller than the average value in the Galaxy as inferred from the boron-to-carbon ratio (B/C) measurements [2]. Thus, the slow diffusion measured by HAWC must not be universal in the Galactic interstellar medium (ISM). It is more likely to be happened only in the vicinity of the cosmic-ray sources like Geminga.

The most straightforward interpretation of the slow diffusion is that the large particle flux near the source leads to the resonant growth of Alfvén waves, which in turn scatter the particles and therefore suppress the diffusion speed. We call it the self-confined scenario, which is often discussed for supernova remnants (SNRs) [3, 4]. While due to the proper motion of Geminga pulsar, it has already left 70 pc away from its birthplace [5], which means the observed slow-diffusion region must not be formed in the early age of Geminga. The injection power of Geminga in the present day should be much weaker than that in the early time. We will show in Section 2 that the electrons released at the late age of Geminga are too few to remarkably suppress the diffusion coefficient as observed by HAWC.

Apart from the self-confined scenario, the slow-diffusion region around Geminga could also be a preexisting structure. The diffusion coefficient inside an SNR should be significantly smaller than that of the ISM, as this region has been swept by the blast wave and acquired more turbulent energy. If the progenitor of Geminga is in a rarefied circumstance, the present scale of the SNR could be large enough to include Geminga and the halo inside. Then Geminga could be embedded in a region with small diffusion coefficient, which explains the observed γ-ray halo. In Section 3, we will check if the SNR is energetic enough to produce the required slow-diffusion region.

2. The self-confined diffusion scenario

A large density gradient of cosmic-ray particles can induce the streaming instability, which will amplify the Alfvén waves in background plasma [6]. To derive the diffusion coefficient in the vicinity of Geminga, we must simultaneously solve the equations of particle transportation and the evolution of Alfvén waves. Here we consider an optimistic scenario for the turbulence growth where the energy loss of electrons and the Alfvén wave dissipation are both ignored.

The propagation equation without cooling term is expressed as

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial x}\left(D\frac{\partial N}{\partial x}\right) = Q\,, \tag{2.1}$$

where x is the coordinate along the initial regular magnetic field lines, N is the differential number density of electrons, D is the diffusion coefficient, and Q is the source function. The power spectrum of Alfvén waves is denoted with W, which is defined by $\int W(k)dk = \delta B^2/B_0^2$, where k is the

---

[1] *Electrons* will denote both electrons and positrons hereafter.

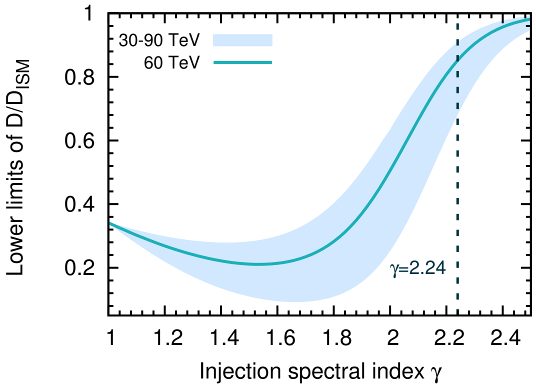

Figure 1: The lower limit of the diffusion coefficient around Geminga under the self-confinement scenario. The solid line is the case of 60 TeV, which is the mean energy of the parent electrons of the γ rays observed by HAWC. The band shows the lower limit of diffusion coefficient varying from 30 to 90 TeV, corresponding to the energy range of HAWC observation. The dotted line marks the injection spectral index provided by HAWC.

wave number, B_0 is the mean magnetic field strength, and δB is the turbulent magnetic field. The pure growth of W can be calculated by

$$\frac{\partial W}{\partial t} = \Gamma_{\rm cr} W = -\frac{4\pi v_A E_{\rm res}^2}{3B_0^2 k} \nabla N(E_{\rm res}) \,, \tag{2.2}$$

where $\Gamma_{\rm cr} = -4\pi v_A E_{\rm res}^2/(3B_0^2 kW)\nabla N(E_{\rm res})$ is the growth rate [6], v_A is the Alfvén speed, and $E_{\rm res}$ is the energy of electrons satisfying $r_g(E_{\rm res}) = 1/k$, where r_g is the Larmor radius of electrons. This expression of $\Gamma_{\rm cr}$ is also applicable for the streaming of electron-positron pairs [7]. The diffusion coefficient is related with W by

$$D(E_{\rm res}) = \frac{1}{3} r_g c \cdot \frac{1}{kW(k)} \,. \tag{2.3}$$

Assuming Geminga pulsar is a point-like source at $x = 0$, then we derive the following expression for $x > 0$ from Eq. (2.1) to (2.3):

$$D(x) = D_{\rm ISM} \exp\left(-\frac{4\pi e v_A E}{B_0 c} \int_x^\infty N dx'\right) \,, \tag{2.4}$$

with $D_{\rm ISM} = D(\infty)$. As $v_A = B_0/\sqrt{4\pi\rho_i}$, the relation is independent B_0. The ambient ion density of Geminga is derived to be 0.02 atoms cm^{-3} [8].

The upper limit of $\int_x^\infty N dx'$ is decided by the source function: $2S\int_x^\infty N dx' < \iint Q dt dx$, where S is the cross section of the one-dimensional flux tube for the released electrons. Obviously a smaller S leads to a stronger wave growth, so we assume a 1 pc scale for the tube. We assume a power-law energy dependency for the source function as $Q \sim E^{-\gamma}$, from 1 GeV to 500 TeV. The time profile of the source function is often assumed to be consistent with that of the spin-down luminosity of the pulsar: $Q \sim (1 + t/\tau_0)^{-2}$, where $\tau_0 = 10$ kyr. The age and the spin-down luminosity of Geminga pulsar can be found in the ATNF catalog[2]. We assume all the spin-down energy is converted to

---

[2] http://www.atnf.csiro.au/research/pulsar/psrcat

the injected electrons. However, as mentioned above, the current slow-diffusion region should be newly formed considering the proper motion of Geminga. So we assume the electrons injected during the last third of Geminga age contribute to the generation of the slow-diffusion region; this should also be an optimistic assumption. Finally the lower limit of the diffusion coefficient is obtained, and we show it in Fig. 1 for varying γ.

The Geminga γ-ray halo measured by HAWC is mainly emitted by electrons with energy around 60 TeV. Fig. 1 indicates that the diffusion coefficient can at most be reduced to $\sim$0.2 times of $D_{\rm ISM}$ in this energy, while the HAWC observation requires hundreds times of suppression. It clearly demonstrates that the self-confined mechanism cannot serve as the main reason for the slow diffusion around Geminga.

3. Slow diffusion inside the SNR

The parent SNR of Geminga has not been identified so far. So we first give an estimate of the possible scale of the Geminga SNR. We adopt the calculator provided by [9]. The SNR dynamic evolution is decided by the parameters such as the initial energy of the ejecta, the eject mass, and the density of the ISM $n_{\rm ISM}$. We note that Geminga is in the southeast of Monogem Ring on the sky map (in the Galactic coordinate), and the distance of Monogem Ring is believed to be similar with that of Geminga. The ISM density in the south of Monogem Ring is derived to be 0.034 cm^{-3} [10], so we assume the same ambient density for the parent SNR of Geminga. Then for typical initial energy of 1×10^{51} erg and ejecta mass of $1.4M_{\odot}$, the current scale of the SNR is 90 pc. This size is large enough to include Geminga pulsar and the TeV halo inside even considering the 70 pc movement of the pulsar. We may envisage a scenario in which Geminga has been chasing the SNR shock, as presented in the left of Figure 2.

The turbulent energy should be mainly generated in the very early age of an SNR, as the shock speed rapidly decreases after the ejecta dominated stage. For our parameter setting, the transition age of Geminga SNR from the ejecta dominated stage to the Sedov-Taylor stage is $\sim$ 850 yr, which is negligible compared with the current age of Geminga. So it is reasonable to consider a burst-like injection for the turbulent energy. For simplicity, we assume that the turbulent energy is injected homogeneously into the SNR. Then we write the evolution equation of the magnetic field turbulence as

$$\begin{cases} \dfrac{\partial W}{\partial t} = \dfrac{\partial}{\partial k}\left(D_{kk}\dfrac{\partial W}{\partial k}\right) \\ W(0,k) = Q_W\delta(t)\delta(k-k_0)+W_{\rm ISM} \end{cases}, \tag{3.1}$$

where we assume the evolution is dominated by the turbulent cascading, with the Kolmogorov type diffusion coefficient $D_{kk}=0.052\,v_A k^{7/2}W^{1/2}$ [11]. The wave damping due to the ion-neutral interaction is not significant for a high ionization environment [12]. We assume the injection scale of the MHD turbulence to be $l_0 = 10$ pc, corresponding to $k_0 = 0.1$ pc^{-1}. The normalization of the injection term is expressed by $Q_W = (\eta E_0/V_0)/(B_0^2/8\pi)$, where η is the conversion efficiency of the magnetic field turbulence, and $V_0 = 4\pi l_0^3/3$. Of course with the expansion of the SNR, the turbulent energy injected in the early should be diluted. To compare with the observation, we assume that the turbulent energy is now homogeneously distributed in a shell 50−90 pc from the SNR center, which includes the Geminga halo in. For an old SNR, the mass is indeed distributed in the outer part, and so does the turbulence. The turbulent energy density is then diluted from W to $W \times V_0/V_{\rm sh}$.

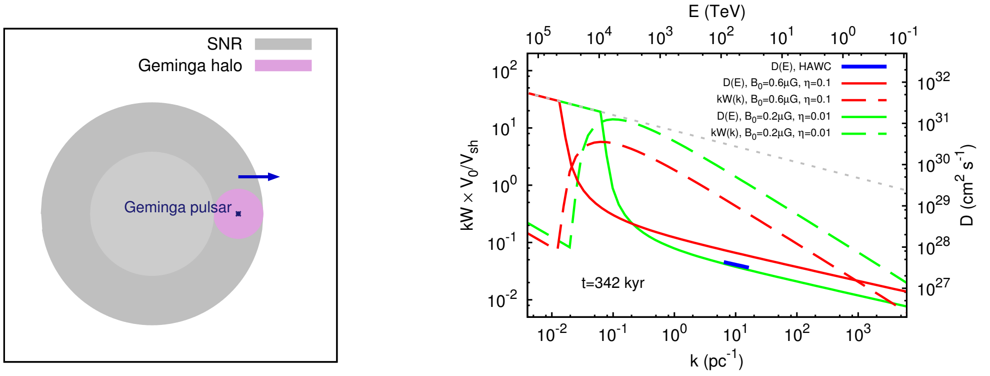

Figure 2: Left: the sketch of the scenario introduced in Section 3. The arrow denotes the direction of the proper motion of Geminga pulsar. In the calculation of Section 3, the magnetic field turbulence is assumed to be distributed in the dark-gray shell. Right: the present-day turbulence spectrum inside the Geminga SNR and the corresponding diffusion coefficient, compared with the diffusion coefficient observed by HAWC. The gray dotted line is the diffusion coefficient in the ISM. Two different parameter sets are adopted: $B_0 = 0.6$ μG, $\eta = 10\%$ (red); $B_0 = 0.2$ μG, $\eta = 1\%$ (green).

The current diffusion coefficient corresponding to $W \times V_0/V_{\rm sh}$ is shown in the right of Figure 2. We show two cases with different magnetic field: $B_0 = 0.6$ μG (corresponds to a current rms magnetic field of 3 μG) and $B_0 = 0.2$ μG (corresponds to a current rms magnetic field of 1 μG). For the former case, the derived $D(E)$ can be close to the value reported by HAWC with $\eta = 10\%$. While for the latter, the theoretical $D(E)$ can accommodate the observed value only with a conversion efficiency of 1% for the magnetic field turbulence. The results indicate that the SNR is energetic enough to explain the inefficient diffusion environment of Geminga. Besides, the required conversion efficiency η is positively correlated with B_0.

4. Other TeV halos

Besides Geminga there are other pulsars that are observed to be surrounded by slow diffusion halos in TeV. The other slow-diffusion halo observed by HAWC along with Geminga is associated with PSR B0656+14. Unlike Geminga, the host SNR of PSR B0656+14, namely the Monogem Ring, is still observable in X-ray, as it is much younger than Geminga ($\sim$100 kyr). As Monogem Ring is an extended structure with a scale of ~ 80 pc [10], the TeV halo of PSR B0656+14 should still be included by the SNR. Other extended TeV halos, such as Vela X and HESS J1825-137, could also be explained by the scenario of Section 3.

On the other hand, we pay attention to another source PSR B1957+20, around which no TeV structure has been detected so far. PSR B1957+20 is definitely traveling in the ISM now. The bow-shock PWN associated to the pulsar has been detected by *Chandra* 0.3–8 keV [13], and the magnetic field of PWN is estimated to be 17.7 μG [14]. This implies that the PWN can accelerate electrons to tens of TeV. Besides, according to the criterion given by [15], TeV structure ought to be revealed around PSR B1957+20 once the accelerated electrons are effectively confined near the source. However, the VHE electrons may not be able to bound themselves by the self-generated waves, unlike the case inside SNR. Thus, the non-detection of VHE emission can be understood.

5. Conclusion

Intuitively, the slow diffusion region Geminga may either be self-generated by the released electrons or be a preexisting structure that is not induced by Geminga. Considering the proper motion of Geminga, we verify that the mechanism of self-generated Alfvén waves due to the streaming instability cannot work to produce such a low diffusion coefficient, as Geminga is too weak to generate enough high energy electrons at the late age. We further propose a scenario that Geminga is still inside its unidentified parent SNR, which may provide a preexisting turbulent environment for it. Our calculation indicates that the diffusion coefficient observed by HAWC can be reproduced if 1-10% of the initial energy of the SNR is converted into the magnetic field turbulence.

Residing inside the parent SNR may not be the unique picture for the preexisting-type interpretation. It is also possible that Geminga is now running into the stellar-wind bubble that creates the Gemini Hα Ring [16]. The stellar wind from the several OB type stars can provide adequate and continuous energy for the turbulence generation. Recently another interpretation of Geminga TeV halo was proposed that it is not attributed to the strong turbulence, but to the anisotropy diffusion of the electrons along the local regular magnetic field [17]. More TeV halos are waited to be found and studied, which will further unveil the origin of the anomalously slow diffusion.

References

[1] Abeysekara, A. U., Albert, A., Alfaro, R., *et al.*, *Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth*, *Science* **358** (2017) 911 [arXiv:1711.06223].

[2] Aguilar, M. and Ali Cavasonza, L. and Ambrosi, G., *et al.*, *Precision Measurement of the Boron to Carbon Flux Ratio in Cosmic Rays from 1.9 GV to 2.6 TV with the Alpha Magnetic Spectrometer on the International Space Station*, *Physical Review Letters* **117** (2016) 231102.

[3] Ptuskin, V. S. and Zirakashvili, V. N. and Plesser, A. A., *Non-linear diffusion of cosmic rays*, *Advances in Space Research* **42** (2008) 486.

[4] Malkov, M. A. and Diamond, P. H. and Sagdeev, R. Z. and Aharonian, F. A. and Moskalenko, I. V., *Analytic Solution for Self-regulated Collective Escape of Cosmic Rays from Their Acceleration Sites*, *ApJ* **768** (2013) 73 [arXiv:1207.4728].

[5] Faherty, J. and Walter, F. M. and Anderson, J., *The trigonometric parallax of the neutron star Geminga*, *Ap&SS* **308** (2007) 225.

[6] Skilling, J., *Cosmic Rays in the Galaxy: Convection or Diffusion?*, *ApJ* **170** (1971) 265.

[7] Evoli, Carmelo and Linden, Tim and Morlino, Giovanni, *Self-generated cosmic-ray confinement in TeV halos: Implications for TeV γ -ray emission and the positron excess*, *Physical Review D* **98** (2018) 063017 [arXiv:1807.09263].

[8] Caraveo, P. A. and Bignami, G. F. and De Luca, A., *et al.*, *Geminga's Tails: A Pulsar Bow Shock Probing the Interstellar Medium*, *Science* **301** (2003) 1345.

[9] Leahy, D. A. and Williams, J. E., *A Python Calculator for Supernova Remnant Evolution*, *AJ* **153** (2017) 239 [arXiv:1701.05942].

[10] Knies, J. R. and Sasaki, M. and Plucinsky, P. P., *Suzaku observations of the Monogem Ring and the origin of the Gemini H α*, *MNRAS* **477** (2018) 4414.

[11] Miller, J. A. and Roberts, D. A., *Stochastic Proton Acceleration by Cascading Alfven Waves in Impulsive Solar Flares*, *ApJ* **452** (1995) 912.

[12] Kulsrud, R. M. and Cesarsky, C. J., *The Effectiveness of Instabilities for the Confinement of High Energy Cosmic Rays in the Galactic Disk*, *ApJL* **8** (1971) 189.

[13] Stappers, B. W. and Gaensler, B. M. and Kaspi, V. M. and van der Klis, M. and Lewin, W. H. G., *An X-ray nebula associated with the millisecond pulsar B1957+20*, *Science* **299** (2003) 1372 [astro-ph/0302588].

[14] Huang, R. H. H. and Kong, A. K. H. and Takata, J., *et al.*, *X-Ray Studies of the Black Widow Pulsar PSR B1957+20*, *ApJ* **760** (2012) 92 [arXiv:1209.5871].

[15] Aharonian, F. A. and Atoyan, A. M. and Kifune, T., *Inverse Compton gamma radiation of faint synchrotron X-ray nebulae around pulsars*, *MNRAS* **291** (1997) 162.

[16] Fang, Kun and Bi, Xiao-Jun and Yin, Peng-Fei, *Possible origin of the slow-diffusion region around Geminga*, [arXiv:1903.06421].

[17] Liu, Ruo-Yu and Yan, Huirong and Zhang, Heshou, *Understanding the multiwavelength observation of Geminga's TeV halo: the role of anisotropic diffusion of particles*, [arXiv:1904.11536].