Constraints on dark matter annihilation with electron spectrum from VERITAS

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Abstract. Cosmic-ray electrons (and positrons) can be used to probe self-annihilation or decay of dark matter particles. We have used spectrum of high energy cosmic-ray electrons between 300 GeV and 5 TeV measured by Very Energetic Radiation Imaging Telescope Array System (VERITAS) to constrain dark matter annihilation cross-section in the solar neighbourhood. A diffusion-loss equation with a canonical model has been used as a spectrum model function by assuming a NFW profile for the Milky Way halo. We have considered cosmic-ray electrons as products of annihilation of heavy dark matter particles (GeV - TeV). During the propagation through interstellar medium, the cosmic-ray electrons lose their energy due to synchrotron radiation, inverse-Compton scattering and ionization processes.

1. Introduction
Dark matter particles are predicted to annihilate or decay into standard model particles that constantly bombarding the Earth’s atmosphere. The standard model particles signatures can be used as a probe of dark matter at our solar neighbourhood. Weakly Interactive Massive Particles (WIMPs) are the most common type of dark matter particle candidates due to its huge range of masses from $\sim$ 1 GeV to 100 TeV. The recent measurement of cosmic-ray electrons spectrum from VERITAS suggested the possibility that such a signature might be detected.

In this work, we focus on dark matter annihilation into electrons and positrons. Since the cosmic-ray electrons quickly lose their energy during propagation into the interstellar medium (ISM) via synchrotron radiation, inverse-Compton scattering and ionization processes, the propagation of electrons is explained by a diffusion-loss equation.

2. Method
2.1. Electron-positron propagation
A diffusion-loss equation has been used to determine the propagation of electrons and positrons through the interstellar medium (ISM),

$$\frac{\partial}{\partial t} \frac{dn}{d\gamma}(x, \gamma) = \nabla \left[ K(x, \gamma) \nabla \frac{dn}{d\gamma}(x, \gamma) \right] + \frac{\partial}{\partial \gamma} \left[ b(x, \gamma) \frac{dn}{d\gamma}(x, \gamma) \right] + Q(x, \gamma). \quad (1)$$

Assuming a diffusion coefficient as $K(\gamma) = K_0 \gamma^\delta$. The energy loss rate $b(x, \gamma)$ is a sum over implicated physical processes, i.e. inverse-Compton scattering, synchrotron radiation, Coulomb
collisions, bremsstrahlung and ionization. The source term \( Q(x, \gamma) \) represents the electron-positron injection rate.

Electron-positron propagation reach a steady-state distribution when giving enough time. Assuming a spherically-symmetric source, the spatial integral can be reduced to one dimension, then the electron-positron spectrum is given by the expression

\[
\frac{dn}{d\gamma}(r, \gamma) = \frac{1}{b(\gamma)} \exp \left(-\frac{r^2}{2\Delta \lambda^2} \right) \times \left\{ \int_0^\infty d\gamma_0 \int_0^\infty dr_0 \exp \left(-\frac{r_0^2}{2\Delta \lambda^2} \right) \times \left[ \exp \left(\frac{rr_0}{\Delta \lambda^2} \right) - \exp \left(-\frac{rr_0}{\Delta \lambda^2} \right) \right] Q(r, \gamma_0) \right\},
\]

where \( \gamma \) and \( \gamma_0 \) are the Lorentz factors of the annihilation products energy \( E_\gamma = \gamma m_e c^2 \) and the injection energies \( E_0 = \gamma_0 m_e c^2 \), the position of the Sun \( r = 8.5 \) kpc. \( \Delta \lambda^2 \) is related to the characteristic diffusion length of the electrons and positrons, \( \Delta \lambda^2 = \lambda^2(\gamma) - \lambda^2(\gamma_0) \), and the variable \( \lambda \) is defined as

\[
\lambda^2(\gamma) = \int_\gamma^\infty \frac{2K(\gamma)}{b(\gamma)} d\gamma.
\]

2.2. Loss rate
Cosmic-ray electrons and positrons expeditiously lose their energy due to physical processes. The inverse-Compton scattering (ICS) of cosmic microwave background (CMB), starlight and infrared photons, synchrotron radiation and ionization of neutral hydrogen atoms.

High-energy electrons and positrons mainly lose their energies by ICS \[1\]

\[
b_{ICS}(\gamma) = \frac{4}{3} \frac{\sigma_T}{m_e c} \gamma^2 U_{rad}
\]

where \( \sigma_T \) is the Thompson cross-section, \( U_{rad} \) is the summation of radiation energy density of CMB, starlight (SL) and infrared (IR) radiation from thermal dust emission \[2\],

\[
U_{rad} = \frac{4\sigma_{SB}}{c} \left( T_{CMB}^4 N_{SL} T_{SL}^4 + N_{IR} T_{IR}^4 \right)
\]

where \( T_i \) and \( N_i \) are the effective temperature and the normalization of each component, respectively, and \( \sigma_{SB} \) is the Stefan-Boltzmann constant.

Synchrotron radiation is an effective loss mechanism at high energies

\[
b_{syn}(\gamma) = \frac{4}{3} \frac{\sigma_T}{m_e c} \gamma^2 U_B
\]

where the magnetic energy density \( U_B = B^2/8\pi \), \( B \) is the intensity of the magnetic field.

The other energy losses come from the ionization of hydrogen atoms, the loss rate is given by \[3\]

\[
b_{ion}(\gamma) = \frac{q_e^2 n_H}{8\pi e_0^2 m_e c^3} \sqrt{1 - \frac{1}{\gamma^2}} \times \left[ \ln \left( \frac{\gamma(\gamma^2 - 1)}{2} \right) - \frac{2}{\gamma} \ln 2 + 1 + \frac{1}{\gamma^2} \right]^{1/2}
\]

where \( n_H \) is the number density of hydrogen atoms, \( q_e \) is the electron charge and \( I \) is the ionization energy of hydrogen atom.
2.3. Source term

In our model, we assume that electrons (and positrons) can be produced by dark matter annihilation,

\[ Q(r, \gamma) = n_{dm}(r) n_{dm*}(r) \langle \sigma v \rangle_{e^\pm} \frac{dN_{e^\pm}}{d\gamma}(\gamma) \]  

(8)

where \( n_{dm} \) and \( n_{dm*} \) denote the number densities of dark matter particles and anti-particles, respectively, \( \langle \sigma v \rangle_{e^\pm} \) is the thermal average of the annihilation cross-section times the dark matter relative velocity, and \( \frac{dN_{e^\pm}}{d\gamma}(\gamma) \) is the injection spectrum of electrons and positrons in the final state. Since we only consider electrons from dark matter annihilation, we assume that \( \frac{dN_{e^\pm}}{d\gamma}(\gamma) = 1 \) per annihilation and for self-conjugate dark matter particles, \( n_{dm} = n_{dm*} = \frac{\rho_{dm}(r)}{m_{dm}}. \)

Since electrons and positrons are injected with the same initial energy \( \gamma_0 \sim m_{dm}/m_e \),

\[ Q(r, \gamma) = Q_0(\gamma) \delta(\gamma - \gamma_0) \]  

(9)

where

\[ Q_0(\gamma) = \frac{1}{2} \left( \frac{\rho_{dm}(r)}{m_{dm}} \right)^2 \langle \sigma v \rangle_{e^\pm} \]  

(10)

is a local production rate of electron-positron pair, the factor 1/2 is added in order to avoid double counting, and \( \delta(\gamma - \gamma_0) \) denote a Dirac delta function.

We consider NFW profile [4] to describe the dark matter density \( \rho_{dm}(r) \)

\[ \rho_{dm}(r) = \frac{\rho_s}{r/r_s \left(1 + \frac{r}{r_s}\right)^2} \]  

(11)

where \( r_s \) and \( \rho_s \) are a characteristic density and radius of the halo, respectively.

2.4. Astrophysical parameters

In our canonical model, the cosmic-ray electrons are eventually reaching Earth after diffusing through the ISM and the Galactic magnetic field. The ISM is mostly neutral with non-ionized hydrogen atoms (\( X_{ion} = 0 \)) of number density \( \sim 1 \text{ cm}^{-3} \), and the Galactic magnetic field of intensity \( B \sim 6 \mu \text{G} \) throughout the Galaxy. Thus, NFW profile with \( r_s = 17 \text{ kpc} \) and \( \rho_s c^2 = 0.35 \text{ GeV cm}^{-3} \), the local dark matter density \( \rho_{dm}(r_\odot)c^2 = 0.3 \text{ GeV cm}^{-3} \). For the diffusion coefficient, we consider the MED model discussed by [5].

2.5. Observational data

For the purpose of constraint the dark matter annihilation in solar neighborhood, we consider the cosmic-ray electrons spectrum measured by VERITAS in 2018 [6]. The data were collected with the VERITAS array in southern Arizona at 31° 40′ N, 110° 57′ W. There is an energy spectrum of cosmic-ray electrons between 300 GeV and 5 TeV. The data set constituting 296 hours of live time and the range of zenith angles between 15 and 25 degrees.

3. Result

We consider the mass of the dark matter particle from 300 GeV to 5 TeV. The constraints on dark matter annihilation are derived by comparing the predictions of an analytic model of electron spectrum and VERITAS data. The upper limits of dark matter annihilation cross-section times the dark matter relative velocity, \( \langle \sigma v \rangle_{e^\pm} \), as a function of dark matter energy \( E_0 \) are shown in figure 1.

The upper limits are quite constant with the value of \( \langle \sigma v \rangle_{e^\pm} \approx 10^{-23} \text{ cm}^3\text{s}^{-1} \) for the mass of the dark matter particle from 300 GeV to 5 TeV. The results are compatible with the previous
works [7, 8] which have estimated the upper limits of dark matter annihilation by using data of electrons and positrons from the other Cerenkov telescope such as HESS [9]. However, our upper limits are higher than the upper limits obtained from gamma-ray data such as Fermi-LAT by factor of 10 [8, 10].

Moreover, the upper limits of dark matter annihilation cross-section times the dark matter relative which we have obtained from VERITAS data is much higher than the thermal cross-section, \( \langle \sigma v \rangle_{e^\pm} = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \), which have been calculated from dark matter relic density. Although dark matter candidates such as WIMPs are not excluded from a possible source of electrons in the solar neighborhood, the higher annihilation rate or a boost factor such as higher density of of dark matter are required. On the other hand, subtraction models of other astrophysical sources which produce electrons can also improve the situation by decreasing the upper limits to be closer to the thermal cross-section.

![Figure 1. Upper limits on the dark matter annihilation cross-section times the dark matter relative velocity. The blue shade area shows the excluded value of dark matter annihilation cross-section obtained from the measurement of the cosmic-ray electrons spectrum by VERITAS. The dash line indicates the value of \( \langle \sigma v \rangle_{e^\pm} = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \).](image)

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