

Constraints on Dark Matter Annihilation by Synchrotron Emission based on Planck Data

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Abstract. Synchrotron emission can be a good probe for dark matter particles in the Milky Way. We have investigated the production of electrons and positrons in the Milky Way within the context of dark matter annihilation. Upper limits on the relevant cross-section are obtained by comparing synchrotron emission in the microwave bands with Planck data. According to our results, the dark matter annihilation cross-section into electron-positron pairs should not be higher than the canonical value for a thermal relic if the mass of the dark matter candidate is smaller than a few GeV. In addition, we also look for constraints on the inner slope of dark matter density profile in the Milky Way. Our results indicate that the inner slope of dark matter profile is between 1 to 1.5.

1. Introduction

Dark matter can be indirectly detected through the signatures of standard model particles produced by its annihilation or decay, see e.g. [1]. The recent results from indirect detection experiments in the solar neighbourhood have suggested the possibility that such a signature has been seen. In particular, the PAMELA experiment has pointed a significant excess of electrons and positrons above the expected smooth astrophysical background [2]. If these results are interpreted in terms of dark matter annihilation, then an abundant population of high-energy e^\pm is being created everywhere in the Galactic dark matter halo, with the associated synchrotron emission in the Galactic magnetic field.

The present work focuses on the astrophysical signatures of dark matter annihilation into electron-positron pairs. We try to impose constraints on the relevant cross-section and on the dark matter density profile by comparing the predictions of an analytic model of synchrotron emission related to dark matter annihilation with a set of observational data obtained from Planck.

2. Method

2.1. Electron-positron propagation

As in our previous work [3][4], we adopt a model-independent approach in which all the injected particles are created with the same initial energy E_0 , of the order of the mass of the dark matter particle. Since electrons and positrons will be relativistic at the moment of their creation, they can efficiently lose their energy through different processes. We will use the Lorentz factor γ to express the energy $E = \gamma m_e c^2$ of the annihilation products, where m_e denotes the rest mass of electron, and c is the speed of light.

The propagation of electrons and positrons through the interstellar medium (ISM) is determined by the diffusion-loss equation

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

We assume a diffusion coefficient of the form $K(\gamma) = K_0 \gamma^\delta$. The energy loss rate $b(\mathbf{x}, \gamma)$ is a sum over the relevant physical processes, i.e. inverse Compton scattering, synchrotron radiation, Coulomb collisions, bremsstrahlung, and ionization. The source term $Q(\mathbf{x}, \gamma)$ represents the instantaneous electron-positron injection rate.

Given enough time, the electron-positron population will approach a steady-state distribution. Considering a spherically-symmetric source, the spatial integral can be reduced to one dimension, and the electron-positron spectrum is finally given by the expression

$$\begin{aligned} \frac{dn}{d\gamma}(r, \gamma) &= \frac{1}{b(\gamma)} \frac{\exp\left(-\frac{r^2}{2\Delta\lambda^2}\right)}{(2\pi r^2 \Delta\lambda^2)^{1/2}} \times \left\{ \int_\gamma^\infty d\gamma_s \int_0^\infty dr_s r_s \exp\left(-\frac{r_s^2}{2\Delta\lambda^2}\right) \right. \\ &\quad \left. \left[\exp\left(\frac{rr_s}{\Delta\lambda^2}\right) - \exp\left(-\frac{rr_s}{\Delta\lambda^2}\right) \right] Q(r_s, \gamma_s) \right\}. \end{aligned} \quad (2)$$

2.2. Source term

The electrons and positrons in our model originate from the annihilation of dark matter particles. We consider a perfectly spherically-symmetric halo, the production rate is dictated by the dark matter number density and the annihilation rate into electron-positron pairs,

$$Q(r, \gamma) = n_{\text{dm}}(r) n_{\text{dm}^*}(r) \langle \sigma v \rangle_{e^\pm} \frac{dN_{e^\pm}}{d\gamma} \quad (3)$$

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 $\frac{dN_{e^\pm}}{d\gamma}$ is the injection spectrum of electrons and positrons in the final state. Assuming all electrons and positrons are injected with the same energy $\gamma_0 \sim m_{\text{dm}}/m_e$,

$$Q(r, \gamma) = Q_0(r) \delta(\gamma - \gamma_0) \quad (4)$$

where

$$Q_0(r) = 2 \left[\frac{\rho_{\text{dm}}(r)}{m_{\text{dm}}} \right]^2 \langle \sigma v \rangle_{e^\pm} \quad (5)$$

is the local production rate per unit volume per unit time and $\delta(\gamma - \gamma_0)$ denotes a Dirac delta function.

For the dark matter density $\rho_{\text{dm}}(r)$, we consider a perfectly spherically-symmetric halo described by a density profile of the form

$$\rho_{\text{dm}}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\alpha \left(1 + \frac{r}{r_s}\right)^{3-\alpha}}, \quad (6)$$

where r_s and ρ_s denote a characteristic density and radius of the halo, respectively, and the α is the inner logarithmic slope of the density profile [5].

2.3. Surface brightness profile

Once the electron-positron spectrum is computed, the emission coefficient¹ for photons of frequency ν is given by the integral

$$j_\nu(r, \nu) = \frac{1}{4\pi} \int_1^\infty \frac{dn}{d\gamma}(r, \gamma) l(\gamma, \nu) d\gamma \quad (7)$$

of the electron-positron spectrum $\frac{dn}{d\gamma}(r, \gamma)$ times the specific luminosity $l(\gamma, \nu)$ emitted at frequency ν by a single electron or positron with Lorentz factor γ . The intensity from any given direction in the sky is simply the integral along the line of sight of the emission coefficient. Since we assume a spherically-symmetric source and boundary conditions, it will only depend on the angular separation θ with respect to the Galactic centre,

$$I_\nu(\theta, \nu) = \int_0^\infty j_\nu(r, \nu) ds, \quad (8)$$

where s represents the distance along the line of sight, and the radial distance r to the centre of the Milky Way at any point along the ray is

$$r = \sqrt{x^2 + y^2}, \quad (9)$$

with $x = s \sin \theta$, $y = s \cos \theta - R_\odot$, and $R_\odot = 8.5$ kpc (the distance of the Sun from the Galactic centre).

The contribution of synchrotron radiation, which dominates at low photon energies, can be estimated as (see e.g.[6])

$$l_{\text{syn}}(\gamma, \nu) = \frac{\sqrt{3} q_e^3 B}{m_e c^2} R[\chi(\gamma)], \quad (10)$$

where m_e and q_e denote the electron mass and charge, respectively, B is the intensity of the magnetic field, and the function $R(\chi)$ is defined as, e.g.[7],

$$R(\chi) \equiv 2\chi^2 \left[K_{\frac{4}{3}}(\chi) K_{\frac{1}{3}}(\chi) - \frac{3}{5} \chi \left\{ K_{\frac{4}{3}}^2(\chi) - K_{\frac{1}{3}}^2(\chi) \right\} \right]. \quad (11)$$

In this expression, K refers to the modified Bessel function, and the normalized frequency

$$\chi \equiv \frac{\nu}{3\gamma^2 \nu_c} \quad (12)$$

is expressed in terms of the cyclotron frequency

$$\nu_c \equiv \frac{q_e B}{2\pi m_e c}. \quad (13)$$

We calculate the electron-positron spectrum as described in expression (2), and then estimate the photon intensity according to expression (8).

2.4. Astrophysical parameters

In our canonical model, the ISM is mainly composed of neutral hydrogen atoms ($X_{\text{ion}} = 0$) with number density $\rho_g/m_p \sim 1 \text{ cm}^{-3}$, and it is permeated by a tangled magnetic field whose intensity is $B \sim 6 \mu\text{G}$ throughout the Galaxy. We use a dark matter density profile with $\alpha = 1$ [5], $r_s = 17$ kpc and $\rho_s c^2 = 0.35 \text{ GeV cm}^{-3}$, consistent with dynamical models of the Milky Way. The virial mass of the Galaxy is thus $10^{12} M_\odot$, and the local dark matter density is $\rho_{\text{dm}}(r_\odot) c^2 = 0.3 \text{ GeV cm}^{-3}$. For the diffusion coefficient, we consider the MED model discussed by [8]. We will also use a model of the ISRF [9] where the photon intensity is represented by grey-body components.

¹ Energy radiated per unit volume per unit frequency per unit time per unit solid angle.

2.5. Observational data

In order to constrain the production of relativistic electrons and positrons in the Milky Way, we consider observations of the whole sky at different wavelengths by using data from 9 channels of Planck observation at microwave wavelengths, which dominated by synchrotron emission. We take the full-resolution coadded temperature maps for each of the 9 frequency bands (30 GHz, 44 GHz, 70 GHz, 100 GHz, 143 GHz, 217 GHz, 353 GHz, 545 GHz and 857 GHz) [10].

3. Results

Once the emission from the Galactic disc and the most prominent point sources is excluded, the remaining spherically-averaged component can be used to place upper limits on the cross-section for dark matter annihilation into electron-positron pairs.

First of all, model intensities are computed according to the scheme described in Section 2.3. We consider the injection energy (i.e. the mass of the dark matter particle) as a free parameter and investigate values of the initial Lorentz factor γ_0 between 2×10^3 and 2×10^7 . We have found that the dark matter annihilation cross-section into electron-positron pairs should not be higher than the canonical value for a thermal relic if the mass of the dark matter candidate is smaller than a few GeV.

By assuming a given value of the cross-section, one can constrain the value of α in expression (6) from the total intensity and the morphology of the observed surface brightness. We set the dark matter annihilation cross-section into electron-positron pairs to the value expected for a thermally-produced relic, $\langle\sigma v\rangle_{e\pm} = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$, and compute the value of α for which the predicted emission rises above the observed level. Our results indicate that the inner slope of dark matter profile α is between 1 to 1.5.

Acknowledgments

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References

- [1] Bertone G 2010 *Particle Dark Matter* (Cambridge: Cambridge University Press)
- [2] Adriani O, et al., PAMELA Collaboration 2009 *Nature*. **458** 607
- [3] Wechakama M, and Ascasibar Y 2011 *MNRAS* **413** 1991
- [4] Wechakama M, and Ascasibar Y 2014 *MNRAS* **439** 566
- [5] Navarro J F, Frenk C S, and White S D M 1996 *ApJ* **462** 563
- [6] Sarazin C L 1999 *ApJ* **520** 529
- [7] Ghisellini G, Guilbert P W, and Svensson R 1988 *ApJL* **334** 5
- [8] Donato F, et al. 2004 *Phy. Rew. D*. **69** 063501
- [9] Cirelli M, and Panci P 2009 *Nuclear Physics B* **821** 399
- [10] Planck Collaboration 2016 *Astronomy & Astrophysics* **594** A1