Indirect evidence of GeV dark matter

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ABSTRACT

Recently, an excess of GeV gamma-ray near the Galactic Centre has been reported. The spectrum obtained can be best fitted with the annihilation of 30–40 GeV dark matter particles through $b\bar{b}$ channel. In this Letter, I show that this annihilation model can also solve the mysteries of heating source in X-ray plasma and the unexpected high gamma-ray luminosity. The cross-section constrained by these observations give excellent agreements with both the predicted range by using Fermi-Large Area Telescope (LAT) data and the canonical thermal relic abundance cross-section.

Key words: dark matter – gamma-rays: galaxies.

1 INTRODUCTION

Recently, high-energy gamma-ray observations reveal some excess emissions near the Galactic Centre. These excess emissions cannot be easily explained by standard physical processes. One potential origin of such emissions is due to an unusual population of millisecond pulsars (Gordon & Macias 2013; Abazajian et al. 2014). However, Daylan et al. (2014) point out that the large diffuse signal of gamma-ray disfavours the possibility of pulsar emissions. Even including both known sources and unidentified sources, the millisecond pulsars can only account no more than 10 per cent of the GeV excess (Hooper et al. 2013). In fact, the majority of discussions of the GeV excess is now focused on the annihilation of dark matter particles (Gordon & Macias 2013; Abazajian et al. 2014; Calore et al. 2014; Daylan et al. 2014; Izaguirre, Krnjaic & Shuve 2014). It is also because the gamma-ray spectrum obtained from Fermi-Large Area Telescope (LAT) data can be well fitted with $b\bar{b}$ annihilation channel of dark matter particles (Abazajian et al. 2014; Daylan et al. 2014). The required cross-section and rest mass of dark matter particle are $(\sigma v) = (1.4–7.5) \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ and $m_b \sim 30–40$ GeV, respectively (Abazajian et al. 2014; Daylan et al. 2014). This cross-section is consistent with the expected canonical thermal relic abundance cross-section $(\sigma v) \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ in cosmology. Furthermore, the inner slope of the radial-dependence of the gamma-ray emissions is $y \approx 1.1–1.3$ (the best fit is $y = 1.26$) (Daylan et al. 2014), which is consistent with the numerical simulation of dark matter halo structure $y = 1–1.5$ (Navarro, Frenk & White 1997; Moore et al. 1999).

In this Letter, I show that the $b\bar{b}$ annihilation channel can also explain the energy required in X-ray emissions in the Galactic Centre. This evidence can further support the dark matter annihilation model and constrain the cross-section and rest mass of the dark matter particles.

2 X-RAY EMISSION AT GALACTIC CENTRE

In the past decade, a large amount of diffuse X-ray data had been obtained by Chandra, BeppoSAX, Suzaku and XMM–Newton (Sidoli et al. 1999; Muno et al. 2004; Sakano et al. 2004; Uchiyama et al. 2013). In particular, Muno et al. (2004) use the data from Chandra to model the temperature of the two components within 20 pc as 0.8 keV (soft component) and 8 keV (hard component). The energy required to sustain the 0.8 and 8 keV components are $3 \times 10^{36}$ and $10^{39}$ erg s$^{-1}$, respectively (Muno et al. 2004). Later, Belmont et al. (2005) point out that the cooling by adiabatic expansion may not be important if the hard component could actually be a gravitationally confined helium plasma. Therefore, the actual energy required for the hard component to balance the radiative cooling would be $(1.4–2.6) \times 10^{39}$ erg s$^{-1}$ within 20 pc (Muno et al. 2004), but not $10^{39}$ erg s$^{-1}$. Although supernova explosions are able to provide such a high energy, it is not possible for supernovae to heat the hard component plasma to such a high temperature (Uchiyama et al. 2013). Also, the correlation between the hard and soft emission suggests that they are produced by related physical processes (Muno et al. 2004). Therefore, the required energy to balance the radiative coolings of both soft and hard component might be given by some other origins. However, there is no widely accepted mechanism to heat and sustain the plasma to such a high temperature (Muno et al. 2004; Uchiyama et al. 2013). One potential explanation is that the heating might result from the viscous friction on molecular clouds flowing towards the Galactic Centre (Belmont et al. 2005).

Here, I propose that the energy given out by annihilation of dark matter particles can explain the energy requirement of both soft and hard components $4.4–5.6 \times 10^{36}$ erg s$^{-1}$ within 20 pc. Although a large amount of energy from annihilation is given out in the form of gamma-ray which is nearly transparent to the plasma, a large amount of high-energy electrons and positrons can also be produced through the $b\bar{b}$ annihilation channel. The spectrum of positron (or electron) energy $dN_e/\text{d}E$ per one annihilation is shown in Fig. 1 (Borriello, Cuoco & Miele 2009; Crocker et al. 2010). These high-energy electrons and positrons would lose their energy and...
give their energy to the plasma mainly by three different processes: ionization loss $\dot{E}_{\text{ion}}$, synchrotron loss $\dot{E}_{\text{syn}}$ and inverse Compton scattering $\dot{E}_{\text{IC}}$. The corresponding energy loss rates are (Longair 1994)

$$\dot{E}_{\text{ion}} = 7.64 \times 10^{-9} \left( \frac{n_e}{1 \text{ cm}^{-3}} \right) \left( 3 \ln - \frac{E}{m_e c^2} + 19.8 \right) \text{ eV s}^{-1}, \quad (1)$$

$$\dot{E}_{\text{syn}} = 6.6 \times 10^{-10} \left( \frac{E}{m_e c^2} \right)^2 \left( \frac{B}{10^{-3} \text{ G}} \right)^2 \text{ eV s}^{-1}, \quad (2)$$

and

$$\dot{E}_{\text{IC}} = 1.6 \times 10^{-9} \left( \frac{E}{m_e c^2} \right)^2 \left( \frac{U_{\text{rad}}}{6 \times 10^3 \text{ eV cm}^{-3}} \right) \text{ eV s}^{-1}, \quad (3)$$

where $U_{\text{rad}}$ is the radiation energy density, $n_e$ and $B$ are the number density of electrons and magnetic field strength in the plasma, respectively. The total number and total energy of positrons or electrons produced per one annihilation are $N_e = \int \langle dN_e / dE \rangle dE \approx 12$ and $E = \int E \langle dN_e / dE \rangle dE \approx 6$–8 GeV, respectively, for $m_e = 30$–40 GeV. Therefore, the average energy for one positron or electron produced is $E \approx 0.5$–0.7 GeV, which gives $E/m_e c^2 \sim 10^4$. Since $n_e \sim 0.1 \text{ cm}^{-3}$ (Muno et al. 2004), $U_{\text{rad}} \sim 10^4 \text{ eV cm}^{-3}$ (Wolfire, Tielens & Hollenbach 1990; Fritz et al. 2014) and $B \sim 10^{-4}$–$10^{-3} \text{ G}$ in the plasma near the Galactic Centre (Crocker et al. 2010), the total energy loss rate is $\dot{E} = \dot{E}_{\text{ion}} + \dot{E}_{\text{syn}} + \dot{E}_{\text{IC}} \sim 10^{-7}$–$10^{-3} \text{ eV s}^{-1}$. The cooling rate would first be dominated by inverse Compton Scattering and synchrotron loss. When the positron or electron is cooled down to about 1 MeV, the cooling rate would be dominated by ionization loss. As a result, the required cooling time is $t_c \sim 10^{12}$–$10^{14}$ s (see Fig. 2).

For the diffusion process of the positrons or electrons, let us first consider the simple random walk model. The stopping distance of a high-energy positron or electron is $d_s \sim \sqrt{r_l \times c t_c}$ (Boehm et al. 2004), where $r_l = E/\epsilon c B$ is the Larmor radius. For $B \sim 10^{-3} \text{ G}$, we have $d_s < 1 \text{ pc}$, which is very small compared with the size of our interested region (20 pc). Therefore, the required cooling time is short enough such that the diffusion process is not important. Nevertheless, Regis & Ullio (2008) suggest that the amplitude of the random magnetic field and the turbulence effect are also important to the diffusion process. This kind of diffusion can be described by a diffusion coefficient $K_0$ and an index $\delta$. For a large scale (greater than 100 pc), the ranges of the values are $K_0 = 10^{27}$–$10^{30} \text{ cm}^2 \text{ s}^{-1}$ and $\delta = 0.3$–0.6 (Delahaye et al. 2008; Regis & Ullio 2008; Lacroix, Boehm & Silk 2014). For the innermost region near the Galactic Centre, the picture is much more uncertain. Regis & Ullio (2008) reveal from the analysis of gamma-ray observations that a significant reduction of the diffusion coefficient in the inner 10 pc region is found. They apply two models, namely Kraichnan and Kolmogorov, to obtain the characteristic diffusion length $d_f$. They get $d_f \sim 10 \text{ pc}$ and $d_f \sim 30 \text{ pc}$ by using the Kraichnan model and Kolmogorov model, respectively. Therefore, not all of the energy of positrons or electrons is lost due to the cooling process during the diffusion within $d_f$. The diffusion length for an electron with initial energy $E_i$ is given by (Fornengo et al. 2012)

$$d_f = \left[ 4 \int_{E_f}^{E_i} \frac{K_i E^3}{E} \frac{dE}{E} \right]^{1/2}, \quad (4)$$

where $E_f$ is the energy of the electron after the diffusion of length $d_f$. Let us consider the lower bounds of the parameters from large scale diffusion $K_0 = 10^{27} \text{ cm}^2 \text{ s}^{-1}$ and $\delta = 0.3$. For $E_i = 0.6 \text{ GeV}$ and $d_f = 20 \text{ pc}$, we get $E_f = 0.2 \text{ GeV}$, which means over 65 per cent of the energy would be lost during the diffusion process.

In the following discussion, we first neglect the effect of diffusion. The result would not be affected if the simple random walk model is the correct diffusion model. However, if either of the other two turbulence models is the correct diffusion model, the calculated cross-section would be at most increased by a factor of 1.5.

The total annihilation rate within $R = 20 \text{ pc}$ is given by

$$\Psi(R) = \int_0^R \rho^2 (\sigma v) m_f^2 4\pi r^2 dr,$$

(5)

Here, $\rho$ is the dark matter density profile, which is assumed to be the generalized NFW profile (Cirelli et al. 2014):

$$\rho = \rho_0 \left( \frac{r}{r_0} \right)^{-\gamma} \left[ \frac{1 + \left( r/r_c \right)}{1 + \left( r/r_0 \right)} \right]^{-\delta - 3\gamma},$$

(6)

where $\rho_0 = 0.3 \text{ GeV cm}^{-3}$, $r_0 = 8.5 \text{ kpc}$ and $r_c = 20 \text{ kpc}$. In our calculations, we assume $\gamma = 1.26$, which is the best fit of the observed gamma-ray spectrum by Fermi-LAT (Daylan et al. 2014). The total energy loss due to electron-positron pairs is $\approx 2 \Psi(R) \times \dot{E}$. Since the energy required to sustain the soft and hard components is $(4.4$–$5.6) \times 10^{36} \text{ erg s}^{-1}$, we can constrain the parameter space of $m_f$ and $(\sigma v)$ by using equation (5) (see Fig. 3). In the plot, we see that the allowed parameter space falls within the range predicted by the annihilation model from Fermi-LAT data $(\sigma v) = (1.4$–$7.5) \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ for $m_f = 30$–$40 \text{ GeV}$.

Figure 1. The energy of a positron or electron as a function of time during cooling process for $B = 10^{-3} \text{ G}$ and $U_{\text{rad}} = 6 \times 10^3 \text{ eV cm}^{-3}$. We have assumed $n_e = 0.1 \text{ cm}^{-3}$ and $E = 0.6 \text{ GeV}$ initially.

Figure 2. The energy of a positron or electron as a function of time during cooling process for $B = 10^{-3} \text{ G}$ and $U_{\text{rad}} = 6 \times 10^3 \text{ eV cm}^{-3}$. We have assumed $n_e = 0.1 \text{ cm}^{-3}$ and $E = 0.6 \text{ GeV}$ initially.
The parameter space constrained by the energy emitted from X-ray plasma is bounded by the solid lines (the simple random walk diffusion model) and the dashed lines (the turbulence model, assumed only 65 per cent of the energy is lost during the diffusion process). The dotted lines are the lower and upper limits of cross-sections obtained from the GeV excess spectrum by using the Fermi-LAT data (Abazajian et al. 2014; Daylan et al. 2014).

For consistency checking, the above result also agrees with the total luminosity of gamma-ray with energy greater than 500 MeV within $R' = 30$ pc in the Galactic Centre detected by the EGRET telescope (Mayer-Hasselwander et al. 1998; Cheng, Chernyshov & Dogiel 2006). The total energy released per one annihilation is given by

$$\dot{E} = 2m_x^{-1}c^2 \int_0^{R'} \rho^2 (\sigma v) 4\pi r^2 dr.$$  \hspace{1cm} (7)

Since the energy carried by neutrinos is negligible (Bergstrom et al. 2005), by using the predicted range of $\langle (\sigma v) \rangle \approx (2-4) \times 10^{-26}$ cm$^3$ s$^{-1}$ from X-ray emission and $m_x = 30–40$ GeV, the total luminosity of gamma-ray is $L_{\gamma} \approx \dot{E} - 2\Psi(R')\dot{E} \approx (2.0 - 2.7) \times 10^{37}$ erg s$^{-1}$, which agrees with the detected luminosity $L = (2.2 \pm 0.2) \times 10^{37}$ erg s$^{-1}$ (Mayer-Hasselwander et al. 1998).

3 DISCUSSION

In this Letter, we show that the annihilation of dark matter particles can satisfactorily explain the energy source of soft and hard components of hot plasma. The cross-section and rest mass of dark matter particles calculated are consistent with the gamma-ray observations and give excellent agreement with the prediction from the annihilation dark matter model. The rest mass and the cross-section could probably be verified by the Large Hadron Collider Experiment in the future.

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