A New Target Object for Constraining Annihilating Dark Matter

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Abstract

In the past decade, gamma-ray observations and radio observations of our Milky Way and the Milky Way dwarf spheroidal satellite galaxies put very strong constraints on annihilation cross sections of dark matter. In this paper, we suggest a new target object (NGC 2976) that can be used for constraining annihilating dark matter. The radio and X-ray data of NGC 2976 can put very tight constraints on the leptophilic channels of dark matter annihilation. The lower limits of dark matter mass annihilating via \( e^+ e^- \), \( \mu^+ \mu^- \), and \( \tau^+ \tau^- \) channels are 200 GeV, 130 GeV, and 110 GeV, respectively, with the canonical thermal relic cross section. We suggest that this kind of large nearby dwarf galaxy with a relatively high magnetic field can be a good candidate for constraining annihilating dark matter in future analyses.

Key words: dark matter

1. Introduction

In the past decade, gamma-ray observations and radio observations gave some stringent constraints for annihilating dark matter. For example, Fermi-LAT observations of the Milky Way center and the Milky Way dwarf spheroidal satellite (MW dSphs) galaxies give tight constraints on annihilation cross sections \( \sigma v \) and dark matter mass \( m \) for some annihilation channels (Abazajian et al. 2014; Ackermann et al. 2015; Calore et al. 2015; Geringer-Sameth et al. 2015; Abazajian & Keeley 2016; Albert et al. 2017; Daylan et al. 2016; Li et al. 2016). Also, radio observations of the Milky Way center put strong constraints on the annihilation cross sections of dark matter (Bertone et al. 2009; Cholis et al. 2015; Cirelli & Taoso 2016). Generally speaking, our galaxy and the MW dSphs galaxies are the most important objects for constraining annihilating dark matter. It is because these objects are local or nearby objects that the uncertainties of observations are generally smaller. Also, most of their properties including dark matter content are well constrained. In particular, the MW dSphs galaxies are promising targets for detection due to their large dark matter content, low diffuse gamma-ray foregrounds, and lack of conventional astrophysical gamma-ray production mechanisms (Ackermann et al. 2014). Therefore, the constraints obtained are usually more stringent so that these objects are commonly believed to be the best targets for constraining annihilating dark matter.

Besides these objects, some recent studies use the data of M31 galaxy, M81 galaxy, and some large nearby galaxy clusters (e.g., Coma, Fornax) to constrain annihilating dark matter (Colafrancesco et al. 2006; Egorov & Pierpaoli 2013; Beck & Colafrancesco 2016; Chan 2016; Storm et al. 2017). These objects generally give similar or less stringent constraints compared with the Fermi-LAT observations of the Milky Way center and the MW dSphs galaxies. In this paper, we explore a new target object (NGC 2976) and use its radio and X-ray data to constrain annihilating dark matter. We show that this object can give very strong constraints for annihilation cross sections, particularly for the following three channels: \( e^+ e^- \), \( \mu^+ \mu^- \), and \( \tau^+ \tau^- \).

2. The X-Ray Constraints

Generally speaking, an electron can increase a photon’s energy from \( E_0 \) to \( \sim \gamma^2 E_0 \) via inverse Compton scattering (ICS), where \( \gamma \) is the Lorentz factor of the electron. If dark matter annihilation gives a large amount of high-energy positrons and electrons (\( \sim 1 \) GeV), these positrons and electrons would boost the energy of the cosmic microwave background (CMB) photons from \( 6 \times 10^{-4} \) eV to about 1 keV. Therefore, these photons can be detected by X-ray observations.

However, this method is difficult to use for normal galaxies and galaxy clusters because these objects usually emit strong X-ray radiation (due to hot gas). Unless we can accurately determine the thermal X-ray emission, the resulting constraints would be quite loose. For dwarf galaxies, this method can give much better constraints as the X-ray emission from dwarf galaxies is usually small (except those having active galactic nuclei). Nevertheless, the size of a typical dwarf galaxy is small (\( R \lesssim 5 \) kpc), so the cooling rate of the high-energy electrons produced from dark matter annihilation is lower than their diffusion rate. Consequently, most of the high-energy electrons escape from the dwarf galaxy without losing most of their energy, and the resulting X-ray signal is suppressed. For example, Colafrancesco et al. (2007) and Jeltema & Profumo (2008) study the X-ray constraints for the local dwarf galaxies and find that the upper bounds of the annihilation cross sections are quite loose.

Fortunately, we discovered a new target object, NGC 2976, which is a good candidate for applying this method. It is a relatively large nearby dwarf galaxy (linear size \( 6 \) kpc, distance \( d = 3.5 \) Mpc). Also, the total X-ray luminosity observed (0.3–8 keV) is \( \sim 10^{36} \) erg s\(^{-1}\), which is much lower than that of other similar objects (\( \gtrsim 10^{38} \) erg s\(^{-1}\) for others; Grier et al. 2011). This relatively low X-ray luminosity can give tighter constraints for annihilating dark matter. Furthermore, the magnetic field strength of NGC 2976 is \( B = 6.6 \pm 1.8 \) \( \mu \)G, which is relatively higher than the local group dwarf galaxies (\( B = 4.2 \pm 1.8 \) \( \mu \)G; Dr兹rga et al. 2016), so the cooling rate of high-energy electrons is higher than the diffusion rate. The cooling timescale for a 1 GeV electron in NGC 2976 is \( t_c = 1/b = 7 \times 10^{15} \) s, while the diffusion
timescale is \( t_0 = R^2/D_0 \sim 10^{17} \), where \( b \approx 1.4 \times 10^{-16} \) is the total cooling rate, \( R = 2.7 \) kpc is the isophotal radius of NGC 2976 (Kennicutt et al. 2003), and we have used a conservative diffusion coefficient \( D_0 = 10^{27} \text{ cm}^2 \text{ s}^{-1} \) (Jeltema & Profumo 2008). Therefore, we ensure that most of the high-energy positrons and electrons produced would lose most of their energy before escaping the galaxy. Since the diffusion process is not very important, the electron number density energy distribution function can be simply given by (Storm et al. 2013)

\[
\frac{d\rho}{dE} = \frac{\langle \sigma v \rangle \rho^2}{2\pi^2 b(E)} \int_b^{E} d\rho' \frac{dN'}{d\rho} d\rho',
\]

where \( \rho \) is the dark matter density profile, \( d\rho'/d\rho \) is the energy spectrum of the electrons produced from dark matter annihilation (Cirelli et al. 2012), and \( b(E) \) is the total cooling rate, which is given by (Colafrancesco et al. 2006)

\[
b(E) = \left[ 0.25E^2 + 0.0254 \left( \frac{B}{\mu G} \right)^2 E \right] \times 10^{-16} \text{ GeV s}^{-1},
\]

with \( E \) in GeV. Here, we neglect the Bremsstrahlung and Coulomb cooling, as the thermal electron number density is very low in NGC 2976.

The number of CMB photons scattered per second from original frequency \( v_0 \) to new frequency \( \nu \) via ICS is given by

\[
I(\nu) = \frac{3 \sigma_T n(v_0) \nu}{16 \gamma^4 \nu_0^3} \times \left[ 2 \nu \ln \left( \frac{\nu}{4 \gamma^2 \nu_0} \right) + \nu + 4 \gamma^2 \nu_0 - \frac{\nu^2}{2 \gamma^2 \nu_0} \right].
\]

where \( \sigma_T \) is the Thomson cross section and \( n(v_0) = 170 \nu^2/(e^x - 1) \text{ cm}^{-3} \) is the number density of the CMB photons with frequency \( v_0 \), where \( x = h \nu v_0/kT_{\text{CMB}} \). The total X-ray energy flux in the energy band \( E_1 \) to \( E_2 \) is given by

\[
\Phi = 2 \times \frac{\langle \sigma v \rangle J}{8\pi m^2} \int_{E_1}^{E_2} d(\hbar \nu) \int_{v_0}^{m} Y(E) \left( \frac{\nu}{E} \right) d\nu \int_0^{\infty} I(\nu) d\nu,
\]

where \( J = \int d\Omega \int_{\cos}^{} \rho^2 d\rho \) is called the \( J \)-factor and

\[
Y(E) = \int_{E}^{m} \frac{dN}{d\rho} d\rho'.
\]

The dark matter density profile \( \rho \) for NGC 2976 can be modeled by

\[
\rho = \rho_0 \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-1},
\]

where \( \rho_0 = 0.198 M_\odot \text{ pc}^{-3} \) and \( r_c = 1 \text{ kpc} \) (Adams et al. 2012). In addition, the substructures in NGC 2976 can greatly enhance the annihilation rate. By using a conservative model of substructure contributions (Molinè et al. 2017), the substructure boost factor is about \( B_{\gamma} = 4.44 \). By considering the dark matter contribution within the isophotal radius \( R = 2.7 \) kpc, we get

\[
\log(J/\text{GeV}^2 \text{ cm}^{-5}) = 17.6. \quad \text{There is another dark matter profile } \rho = \rho_0 (r/1 \text{ pc})^{-0.235} \text{ with } \rho_0 = 0.260 M_\odot \text{ pc}^{-3} \text{ that can produce good fit to the kinematic data of NGC 2976 (Adams et al. 2012). The corresponding } J \text{-factor for this dark matter profile is } \log(J/\text{GeV}^2 \text{ cm}^{-5}) = 17.5. \quad \text{Therefore, the systemic uncertainty of the } J \text{-factor is about 30\%. In the following, since the uncertainty is not very large, we will use the dark matter profile in Equation (7) to perform the analysis. The effect of this uncertainty will be discussed later.}

The total X-ray flux observed (0.3–8 keV) for NGC 2976 is \( \Phi = (0.42 \pm 0.17) \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) (Grier et al. 2011). By assuming that the observed X-ray flux originates from ICS due to dark matter annihilation only, we can obtain the upper limits of the annihilation cross sections for different channels (see Figure 1). Here, we can see that the observed X-ray range is not very good for constraining annihilating dark matter. As we can see from Figure 1, the X-ray constraints are close to the upper bounds obtained by Fermi-LAT observations for \( e^+ e^- \) and \( \mu^+ \mu^- \) channels only (Ackermann et al. 2015). For the thermal relic cross section \( \langle \sigma v \rangle = 2.2 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1} \) (Steigman et al. 2012), the minimum allowed \( m \) for the \( e^+ e^- \) channel is 8 GeV, which is slightly tighter than the Fermi-LAT limit for the Milky Way’s dwarf galaxies (Geringer-Sameth et al. 2015). If we can have better X-ray data or more hard X-ray data, the corresponding constraints would be much tighter.

Note that we have only included the CMB photons in our calculations. In fact, there are other radiation fields in the infrared and visible light bands that can also contribute to the X-ray flux via ICS. Nevertheless, the contribution of other radiation fields in NGC 2976 is small and most of the resulting photons via ICS are in MeV or above bands. Therefore, our results would not be significantly affected by other radiation fields.

### 3. The Radio Constraints

If we assume that all the radio radiation originates from synchrotron radiation of the electron and positron pairs produced by dark matter annihilation, the observed upper limit of the total radio flux can be used to constrain the cross sections of dark matter annihilation. As mentioned above, since the diffusion term can be neglected, the injected spectrum of the electron and positron pairs is proportional to the source spectrum (Storm et al. 2013). By using the monochromatic approximation (the radio emissivity is mainly determined by the peak radio frequency), the total synchrotron radiation energy flux of the electron and positron pairs produced by dark matter annihilation is given by (Bertone et al. 2009; Profumo & Ullio 2010)

\[
S \approx \frac{1}{4 \pi d^2} \left[ \frac{9}{2} \langle \sigma v \rangle \int_0^R 4\pi R^2 \rho^2 E \left( \frac{E}{R} \right) dR \right],
\]

where \( E = 0.43 (\nu/\text{GHz})^{1/2} (B/\text{mG})^{-1/2} \text{ GeV} \) and \( \tilde{b} \approx 1.18 \) is a correction factor if we include the cooling of ICS.

The latest radio observations with the three different frequencies \( \nu = 1.43 \) GHz, \( \nu = 4.85 \) GHz, and \( \nu = 8.35 \) GHz obtain \( 2 - \sigma \) upper bounds of radio fluxes \( S \leq 1.02 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( S \leq 1.59 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively (Drazga et al. 2016). By using Equation (8), we obtain the corresponding upper limits of annihilation cross sections for four popular channels: \( e^+ e^- \), \( \mu^+ \mu^- \), \( \tau^+ \tau^- \), and \( b \bar{b} \)
and positrons would lose their energy within their stopping distance. This suppresses the signals of X-ray and radio fluxes due to dark matter annihilation. The other advantage of using NGC 2976 is that it has tight upper bounds of X-ray fluxes and radio fluxes. These features suggest that NGC 2976 is a very good candidate for constraining annihilating dark matter, particularly for the leptophilic channels. Further observations of NGC 2976 in radio wavelengths and X-ray bands can definitely push the upper bounds of the cross sections to a much tighter level.

In our analyses, we can see that the X-ray constraints of NGC 2976 are not good enough to give tighter constraints compared to the Fermi-LAT gamma-ray constraints. The limitations of using X-ray constraints are still quite large, unless we can fully identify the contribution of non-thermal X-ray emission. Nevertheless, the radio constraints can give much tighter constraints, which is complementary to the gamma-ray constraints. These constraints can rule out some existing models (via $e^+ e^-$, $\mu^+ \mu^-$, or $\tau^+ \tau^-$) of dark matter interpretation of the excess gamma-ray and positrons in our galaxy (Boudaud et al. 2015; Calore et al. 2015).

As we mentioned, NGC 2976 has a high magnetic field $B = 6.6 \pm 1.8 \mu G$ and it is a relatively large dwarf galaxy (linear size = 6 kpc), so the cooling timescale is much shorter than the diffusion timescale. This can maximize the X-ray and radio fluxes due to dark matter annihilation. The other advantage of using NGC 2976 is that it has tight upper bounds of X-ray fluxes and radio fluxes. These features suggest that NGC 2976 is a very good candidate for constraining annihilating dark matter, particularly for the leptophilic channels. Further observations of NGC 2976 in radio wavelengths and X-ray bands can definitely push the upper bounds of the cross sections to a much tighter level.

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Figure 1. Upper limits of the annihilation cross sections for four annihilation channels. The red, green, and blue solid lines represent the upper limits for the radio constraints (red: $\nu = 1.43$ GHz; green: $\nu = 4.85$ GHz; blue: $\nu = 8.35$ GHz). The orange dashed lines represent the upper limits for the X-ray constraints. The black solid lines represent the gamma-ray observations of MW dSphs galaxies with Fermi-LAT (with J-factor uncertainties; Ackermann et al. 2015). The black dashed lines represent the gamma-ray observations of recently discovered Milky Way satellites with Fermi-LAT (only for $\tau^+ \tau^-$ and $b\bar{b}$ channels; Albert et al. 2017). The dotted lines represent the canonical thermal relic cross section for annihilating dark matter (Steigman et al. 2012).
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