The diffuse Galactic $\gamma$-rays from dark matter annihilation

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The diffuse Galactic $\gamma$-rays from EGRET observation shows excesses above 1 GeV in comparison with the expectations from conventional Galactic cosmic ray (CR) propagation model. In the work we try to solve the “GeV excess” problem by dark matter (DM) annihilation in the frame of supersymmetry (SUSY). Compared with previous works, there are three aspects improved in this work: first, the direction-independent “boost factor” for diffuse $\gamma$-rays from dark matter annihilation (DMA) is naturally reproduced by taking the DM substructures into account; second, there is no need for renormalization of the diffuse $\gamma$-ray background produced by CRs; last but not the least, in this work our new propagation model can give consistent results of both diffuse $\gamma$-rays and antiprotons, by directly adding the signals from DMA to the diffuse $\gamma$-ray background. This is a self-consistent model among several possible scenarios at present, and can be tested or optimized by the forthcoming experiments such as GLAST, PAMELA and AMS02.

The diffuse Galactic $\gamma$-rays are produced via interaction of CRs with the interstellar medium and radiation field. However, the spectrum of the diffuse $\gamma$ rays measured by EGRET shows an excess above 1 GeV$^1$ in comparison with the prediction based on the conventional CR model, whose nucleus and electron spectra are consistent with the locally observed data. The discrepancy may indicate large-scale proton or electron spectrum, which determines the diffuse $\gamma$-rays, different than the local measured one, or the existence of exotic sources of diffuse continuum $\gamma$-ray emission.

A harder nucleon spectrum with power-law index of $-2.4 \sim 2.5$ has been proposed in Ref. $^2$ to solve the “GeV excess” problem. However, it has been pointed out that such a hard nucleon spectrum will overproduce secondary antiprotons and positrons $^3$, which has effectively been excluded by recently high energy $\bar{p}/p$ ratio measurements $^4$. A hard electron spectrum is studied in Ref. $^5$ while this hypothesis also suffers difficulties, e.g. it produced too many $\gamma$-rays at higher energies and couldn't be compatible with the local electron spectrum $^6$. For the “optimized model” in $^6$ both the proton and electron injection spectra are “fine-tuned” and their intensities are renormalized to explain the EGRET diffuse $\gamma$ spectra. However, it may be not easy for the proton spectrum to fluctuate significantly and to be different from other heavy nuclei, as introduced in $^6$.

It is shown that the observed peak of the diffuse $\gamma$ spectrum at low galactic latitudes, where the dominant contribution is from pion decay, is at higher energies than the $\pi^0$ decay peak. Further the conventional model with reacceleration is known $^7$ to produce less antiprotons at $\sim 2$ GeV than the measurement at BESS $^8$ by a factor of about 2. Positron data also show some “excess” at higher energies $^9$. These discrepancies may all indicate a contribution from “exotic” sources, e.g. DMA $^{10}$.

de Boer et al. $^{11}$ pointed out that the “GeV excess” could be explained by the long-awaited signal of DMA from the Galactic halo. By fitting both the background spectrum from cosmic nucleon collisions and the signal spectrum from neutralino, the lightest supersymmetric particle, annihilation they found the EGRET data could be well explained in all directions. From the spatial distribution of the diffuse $\gamma$-ray emission they constructed the DM profile, with two rings supplemented on the smooth halo. A direction independent “boost factor” to the signal flux usually at the order of 100 is necessary to explain the $\gamma$-ray excess. Another factor between $1/2 - 2$ for the background flux is also needed to account for the spectra at different directions. However, de Boer’s model with ring profiles and a large boost factor will lead to possible conflict with the antiproton flux, as shown by Bergström et al. $^{12}$.

Based on the model-fitting by de Boer et al. $^{11}$ and Strong’s work $^6$, we try to explain the diffuse $\gamma$-ray spectrum in this work by directly calculating the background and DMA fluxes and to overcome their shortcomings at the same time. By adjusting the propagation parameters we try to give consistent descriptions to the measured spectra without any arbitrary normalization of the background contribution. We calculate the DMA in the frame of the minimal supersymmetric extension of the standard model (MSSM). After taking into account the enhancement by the existence of subhalos $^{13}$ we do not need the “boost factor” any more. Furthermore in our propagation model, we found the antiproton flux is in agreement with the measurements. The crucial point is that the enhancement by subhalos is spatial dependent in the Galactic halo, not “universal” as the previous works adopted. So the enhancement of $\gamma$-ray is different from that of antiproton flux, because the whole halo will contribute to the diffuse $\gamma$-ray intensity, while only antiprotons produced within the diffusion region will contribute to the observed flux. It is found that the same scenario with large boost by subhalos can be used to explain the positron excess $^{14}$.

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The fluxes of DMA products are determined by two independent factors. The first factor is related to the annihilation cross section and determined by particle physics of DM, while the other one is connected with the spatial distribution of DM and determined by astrophysics [10]. We use the package DarkSUSY [15] to calculate the particle physical factor of DMA. Scanning the parameter space of MSSM we find the $\gamma$-ray spectrum with $m_\chi = 40 \sim 50$ GeV can fit the EGRET data well. The branching ratios between neutralino annihilation into $\tilde{\rho}$ and $\gamma$-rays are also calculated for different MSSM parameters and are found to be $1/20 \sim 1/10$ in a wide mass range. We chose a $m_\chi = 48.8$ GeV model which predicts $\Omega h^2 = 0.09$ and $\frac{B(r_{\chi\chi\rightarrow\gamma})}{B(r_{\chi\chi\rightarrow\tilde{\rho}})} \approx 0.055$ for energies above the threshold $E_{th} = 0.5$ GeV. The second factor determining the annihilation fluxes is defined as $\Phi^{\text{astro}} = \int \frac{d^2r}{D} dV$ with $D$ the distance to the source of $\gamma$-ray production, $\rho$ the density profile of DM and $V$ the volume of annihilation taking place. When we consider the contribution from subhalos, the factor is given by the number integral along a direction ($\theta, \phi$), $\Phi_{\text{sub}} = \int_{n.s.} \Phi^{\text{astro}} dN_{\text{sub}}(\theta, \phi)$. We use the simulation result of the subhalo distribution with mass $m_{\text{sub}}$ at the radius $r$ as the NFW [18], Moore [19] or a cuspier form [20] as $N_{\text{sub}}(m_{\text{sub}}, r) = N_0 \left( \frac{4}{3} c^2 \right)^{-1.9} \left( 1 + \left( \frac{r}{r_s} \right) \right)^{-1}$, where $M_v \approx 1.0 \times 10^{12} M_\odot$ is the mass of the Galaxy, $r_H = 0.14 r_v \approx 36$ kpc ($r_v \approx 260$ kpc is the virial radius of the Galaxy halo) is the core radius for the distribution of subhalos, $r$ is the distance to the Galactic center (GC) and $N_0$ is the normalization factor. The minimal subhalos can be as light as $10^{-6} M_\odot$ as shown by the recent simulation conducted by Diemand et al. [13], while the maximal mass of substructures is taken to be $0.01 M_v$ [16]. The tidal effects are taken into account under the "tidal approximation" [16] so that the minimal subhalos are disrupted near the GC. The total signal flux comes from the annihilation in the subhalos and the smooth component.

The DM density profile within each subhalo is taken as the NFW [18], Moore [19] or a cuspier form [20] as $\rho = \frac{\rho_s}{(r/r_s)^\gamma} \left( 1 + \frac{r}{r_s} \right)^{-1}$ with $\gamma = 1.7$. The last form is favored by the simulation conducted by Reed et al. [21], which shows that $\gamma = 1.4 \sim 0.08 \log(M/M_\odot)$ increases for smaller subhalos. We take $\gamma = 1.7$ for the whole range of subhalo masses as a simple approximation. The small halos with large $\gamma \approx 1.5 \sim 2$ are also found by Diemand et al. [13]. To determine the profile parameters, we also need to know the concentration $c_v$ as a function of halo mass. Here we adopted the semi-analytic model of Bullock et al. [22], which describes $c_v$ as a function of virial mass and redshift. We adopt the mean $c_v - m_{\text{sub}}$ relation at redshift zero (see also Fig. 1 of Ref. [14]). The scale radius is then determined as $r_{\gamma \gamma}^{\text{nfw}} = r_v/c_v$, $r_{\gamma \gamma}^{\text{moore}} = r_v^{\text{nfw}}/\sqrt{0.63}$ or $r_{\gamma} = r_v^{\text{nfw}}/(2 - \gamma)$. Another factor determining the $\gamma$-ray flux is the core radius, $r_{\text{core}}$, within which the DM density should be kept constant due to the balance between the annihilation rate and the infalling rate of DM particles [23]. The core radius $r_{\text{core}}$ is approximately in the range $10^{-8} \sim 10^{-7}$ kpc for the $\gamma = 1.7$ profile and $10^{-9} \sim 10^{-8}$ kpc for the Moore profile. In Fig. 1 we show the factor $\Phi^{\text{astro}}$ from the smooth component, the subhalos and the total contribution as a function of the direction to the GC. The $\Phi^{\text{astro}}$ from subhalos is almost isotropic to different directions, this is because the DM distribution is almost spherical symmetric and the Sun is near the GC. We can see that the largest enhancement for $\gamma = 1.7$ subhalos at large angles can reach 2 orders of magnitude and depends on the value of $r_{\text{core}}$; while for the Moore profile the enhancement is about one order of magnitude and for NFW profile only about 3 times larger. The $\Phi^{\text{astro}}$ for Moore and NFW profiles is not sensitive to $r_{\text{core}}$ [16]. We also notice that near the GC there is no enhancement. This is actually a very important difference from the model given by de Boer [11] where the "boost factor" is universal. Given the factor $\Phi^{\text{astro}}$ and the SUSY model we can predict the $\gamma$-ray flux by neutralino annihilation.

We now turn to the calculation of the background diffuse $\gamma$-ray emission, which consists of several components: the neutral pion decay produced by energetic interactions of nuclei with interstellar gas, emission by electrons inverse Compton scattering off the interstellar radiation field, the bremsstrahlung of electrons in interstellar medium, and the extragalactic background. We calculate the background diffuse $\gamma$-rays using the package GALPROP [24] which uses the realistic distributions for the interstellar gas and radiation fields and solves the diffusion equations numerically.

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The diffusion halo height of the propagation is taken as $z_h = 1.5$ kpc, which is different from 4 kpc as adopted in $[6, 11]$. A smaller $z_h$ can effectively lower the $\bar{p}$ flux since it is only $\bar{p}$ from DMA in the diffusion region that can contribute to the flux observed on the Earth. The propagation parameters have been tuned to fit the $B/C$ ratio and the local proton (and electron) spectra, as shown in Fig. 2. A major uncertainty in the models of diffuse Galactic $\gamma$-ray emission is the distribution of molecular hydrogen for the derivation of $H_2$ density from the CO data is problematic $[26]$. For example, the scaling factor $X_{CO}$ from COBE/DIRBE studies by Sodroski et al. $[27]$ is about 2–5 times greater than the value given by Boselli et al. $[28]$ in different Galactocentric radius based on the measurement of Galactic metallicity gradient and the inverse dependence of $X_{CO}$ on metallicity, which is normalized to the $\gamma$-ray data $[26]$. An analysis of EGRET diffuse $\gamma$-ray emission yields a constant $X_{CO} = (1.9 \pm 0.2) \times 10^{20}$cm$^{-2}$/(K km s$^{-1}$) for $E_\gamma = 0.1 - 10$ GeV $[24]$. Observations of particular local clouds yield lower values $X_{CO} = 0.9 - 1.65 \times 10^{20}$ cm$^{-2}$/(K km s$^{-1}$). Since the fit to the EGRET data for $E_\gamma = 0.1 - 10$ GeV in $[24]$ assumes only the background contributions, we expect they give larger $X_{CO}$ than the case with new components, such as the consideration here. We find a smaller $X_{CO} = 0.6 \sim 1.0 \times 10^{20}$ molecules cm$^{-2}$/(K km s$^{-1}$) can give much better fit to the EGRET data below 1 GeV. We take $X_{CO}$ a constant independent of the radius $R$. As shown in Ref. $[24]$, the simple form is compensated by an appropriate form of the CR sources. We have taken the radial distribution of CR sources in the form of $(r/r_o)^\alpha e^{-\beta(r-r_o)/r_o}$ with $\alpha = 1.35$, $\beta = 2.7$, $r_o = 8.5$ kpc, and limiting the sources within $r_{max} = 15$ kpc, which are adjusted to best describe the diffuse $\gamma$-ray spectrum.

The results are shown in Fig. 3 for six different sky regions as defined in $[6]$. It should be noted that including the enhancement by subhalos does not exclude the ring-like structures proposed by de Boer $[11]$. That is natural since taking the subhalos into account only enhances the signals coming from the smooth component but does not mimic the ring-like structure, which can fit the EGRET data at different directions $[11]$. Actually the ring-like structure, such as the tidal stream of dwarf galaxies are not unusual in N-body simulations. Observations and simulations support such an idea that the ring at $\sim 14$ kpc is from the tidal disruption of the Canis Major dwarf galaxy $[30]$. Recent result of the rotation curve also predicts a ring like structure at the similar position $[31]$. From Fig. 3 we can see that the EGRET spectra in all regions are in good agreement with the theoretical values. It should also be noted that in our work we adjust the propagation parameters in GALPROP and do not need an arbitrary normalization of the background $\gamma$ rays as done in $[11]$.

Finally we check the antiproton flux in this model. We first calculate the source term produced by neutralino annihilation adopting the same SUSY model as used for $\gamma$-ray calculation, $\Phi_p(r, E) = \frac{\langle \phi(E) \phi(E) \rangle}{2 m_{\chi}} (\rho(r)^2)$ where $\phi(E)$ is the differential flux at energy $E$ by a single annihilation and $\langle \rho(r)^2 \rangle = \rho_{smooth}^2 + \langle \rho_{sub}^2 \rangle$. The contribution from the subhalos is given by $\langle \rho(r)^2 \rangle_{sub} = \int_{m_{min}}^{m_{max}} N_{sub}(m, r) \left( \int \rho^2 dV \right) \cdot dm$ with $N_{sub}(m, r)$ the number density of subhalos with mass $m$ at radius $r$. We then calculate the propagation of $\bar{p}$ and its spectrum at Earth by incorporating the DMA signals in GALPROP. The propagation parameters are kept the same as the ones in the background $\gamma$-ray calculation.

In Fig. 4 we show the background, signal and total $\bar{p}$ fluxes in our model. The result is much smaller compared with $[12]$. Several ways are incorporated to decrease the $\bar{p}$ flux, while keeping $\gamma$-rays the same. The small $z_h$ in our model helps to suppress the $\bar{p}$ flux from the smooth DM component. The contribution from the rings is found to...
FIG. 3: Spectra of diffuse $\gamma$-rays for different sky regions (top row, regions A, B, middle C, D, bottom E, F). The model components are $\pi^0$ decay, inverse Compton, bremsstrahlung, EGRB and DMA (dark red curve).
be greatly suppressed by slightly adjusting the ring parameters: the inner ring is now located at \( R = 3.5 \) kpc and the outer ring is moved from \( R = 14 \) kpc to 16 kpc. This is because the distance dependence of the propagation \( \bar{p} \) is steeper (exponential decrease) than \( r^{-2} \) of \( \gamma \)-rays \[32\]. It can also be noted that the total \( \bar{p} \) flux in the present model is still a bit higher than the best fit values of the observations at lower energies, however, it is consistent with data within 1\( \sigma \). The large error of the present data make it hard to give definite conclusion now. The future measurement from PAMELA \[33\] or AMS02 \[34\] will finally determine if the present model is confirmed or disproved.

In summary we calculate the Galactic diffuse \( \gamma \)-rays from CR secondaries and DMA. By building a new propagation model and taking into account the enhancement of DMA by subhalos the EGRET data may be explained without any “boost factor”. However, the ring-like structures are still necessary. A lower \( X_{\text{CO}} \) than previously used value is favored and the smaller halo height efficiently decrease the yield of \( \bar{p} \) from DMA. The neutralino mass is in the range \( 40 - 50 \) GeV and very cuspy profile for subhalos are needed. The \( \bar{p} \) flux coming from secondaries (and tertiaries) and from DMA are consistent with present experimental bound in this propagation model by slightly adjusting the ring parameters.

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[1] S. D. Hunter et al., Astrophys. J. 481, 205 (1997).
[2] P. Gralewicz et al., Astron. Astrophysics 318, 925 (1997); M. Mori, Astrophys. J. 478, 225 (1997).
[3] I. V. Moskalenko, A. W. Strong and O. Reimer, Astron. Astrophysics 338, L75 (1998).
[4] A. S. Beach et al., Phys. Rev. Lett. 87, 271101 (2001).
[5] T. A. Porter, R. J. Protheroe, J. Phys. G 23, 1765 (1997); M. Pohl, J. A. Esposito, Astrophys. J. 507, 327 (1999); F. A. Aharonian, A. M. Atoyan, Astron. Astrophysics 362, 937 (2000).
[6] A. W. Strong, I. V. Moskalenko, O. Reimer, Astrophys. J. 613, 962 (2004).
[7] I. V. Moskalenko et al., Astrophys. J. 565, 280 (2002).
[8] S. Orto et al., Phys. Rev. Lett. 84, 1078 (2000).
[9] S. W. Barwick et al., Astrophys. J. 482, 191 (1997).
[10] G. Jungman, M. Kamionkowski, K. Griest, Phys. Rept. 267, 195 (1996).
[11] W. de Boer et al., Phys. Lett. B 636, 13 (2006); Astron. Astrophysics 444, 51 (2005).
[12] L. Bergstrom et al., JCAP 0605, 006 (2006).
[13] J. Diemand, B. Moore, J. Stade, Nature 433, 389 (2005); J. Diemand, M. Kuhlen, P. Madau, astro-ph/0603250.
[14] Q. Yuan and X. J. Bi, JCAP 0705: 001 (2007), astro-ph/0611872.
[15] P. Gondolo et al., JCAP 0407, 008 (2004), astro-ph/0406204.
[16] X. J. Bi, Nucl. Phys. B 741, 83 (2006); X.-J. Bi, Y.-Q. Guo, H.-B. Hu, X. Zhang, Nucl. Phys. B 775, 143 (2007). X. J. Bi, Phys. Rev. D 76, 123511 (2007); J. Lavalle, Q. Yuan, D. Maurin, X. J. Bi, Astron. Astrophysics 479, 427 (2008).
[17] J. Diemand et al., Mon. Not. R. Astron. Soc. 352, 535 (2004); L. Gao, S.D.M. White, A. Jenkins, F. Stoehr, V. Springel, Mon. Not. R. Astron. Soc. 355, 819 (2004).
[18] J. F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. 490, 493 (1997).
[19] B. Moore et al., 499, 5 (1998); MNRAS, 310, 1147 (1999).
[20] S.H. Zhao, Mon. Not. R. Astron. Soc. 278, 488 (1996).
[21] D. Reed et al., MNRAS 357, 82 (2005).
[22] J. S. Bullock et al., MNRAS 321, 559 (2001).
[23] V. Berezinsky et al., Phys. Lett. B 294, 221 (1992).
[24] A. W. Strong, I. V. Moskalenko, Astrophys. J. 509, 212 (1998); A. W. Strong, I. V. Moskalenko, O. Reimer, Astrophys. J. 537, 763 (2000).
[25] I. V. Moskalenko et al., Astrophys. J. 565, 280 (2002).
[26] A. W. Strong et al., Astron. Astrophys. 422, L47 (2004).
[27] T.J. Sodroski et al., Astrophys. J. 480, 173 (1997).
[28] A. Boselli, J. Lequeux, G. Gavazzi, Astron. Astrophys. 384, 33 (2002).
[29] A. W. Strong, J. R. Mattix, Astron. Astrophys. 308, L21 (1996).
[30] D. Martinez-Delgado, D. J. Butler, H. W. Rix, Y. I. Franco, J. Pe narrubia, E. J. Allaro, D. I. Dinescu, As-
trophys. J. 633, 205 (2005); J. Penarrubia, D. Martinez-Delgado, H.W. Rix, M.A Gomez-Flechoso, J. Munn, H. Newberg, E.F. Bell, B. Yanny, D. Zucker, E. K. Grebel, Astrophys. J. 626, 128 (2005); N. F. Martin, R. A. Ibata, M. Bellazzini, M. J. Irwin, G. F. Lewis, W. Dehnen, Mon. Not. Roy. Astron. Soc. 348, 12 (2004).

[31] P. M. W. Kalberla, L. Dedes, J. Kerp, U. Haud, arXiv:0704.3925v1.

[32] D. Maurin, R. Taillet, C. Combet, astro-ph/0609522v3; D. Maurin, R. Taillet, C. Combet, astro-ph/0612714v1; J. Lavalle, Q. Yuan, D. Maurin, X.-J. Bi, Astron. Astrophys. 479, 427 (2008).

[33] see http://wizard.roma2.infn.it/pamela/

[34] see http://ams.cern.ch/