Is the dark matter interpretation of the EGRET gamma excess compatible with antiproton measurements?

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Abstract. We investigate the internal consistency of the halo dark matter model which has been proposed by de Boer et al for explaining the excess of diffuse galactic gamma rays observed by the EGRET experiment. Any model based on dark matter annihilation into quark jets, such as the supersymmetric model proposed by de Boer et al, inevitably also predicts a primary flux of antiprotons from the same jets. Since propagation of the antiprotons in the unconventional, disc-dominated type of halo model used by de Boer et al is strongly constrained by the measured ratio of boron to carbon nuclei in cosmic rays, we investigate the viability of the model using the DarkSUSY package to compute the gamma-ray and antiproton fluxes. We are able to show that their model is excluded by a wide margin from the measured flux of antiprotons. We therefore find that a model of the type suggested by Moskalenko et al, where the intensities of protons and electrons in the cosmic rays vary with galactic position, is far more plausible for explaining the gamma excess.

Keywords: cosmic rays, dark matter, high energy photons, structure of galaxies

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1. Introduction

In a series of papers, de Boer et al [1]–[4] have put forward the idea that the well-known EGRET excess of diffuse galactic gamma rays [5] could be well explained by dark matter annihilations. The idea that excess from the region near the galactic centre may be due to dark matter annihilations has a long history (at least [6]–[8]) but de Boer et al have extended this idea to claim that all the diffuse galactic gamma rays detected above 1 GeV by the EGRET satellite, irrespective of the direction, have a sizable dark matter contribution (for a similar, but less explicit, proposal, see [9]). De Boer et al propose specific supersymmetric models as examples of viable models with correct relic density, and the gamma-ray fluxes are made to fit the observations. The price they have to pay, however, is a rather peculiar dark matter halo of the Milky Way, containing massive, disc concentrated rings of dark matter besides the customary smooth halo. In addition, they have to crank up the predicted gamma-ray flux by considerable ‘boost factors’. We will here examine these hypotheses a bit more closely. In particular, we will discuss the astrophysical properties and possible inconsistencies of the model. We point out that, besides the strange features of the halo model (that we judge difficult to achieve with non-dissipative dark matter), supersymmetric models with large gamma-ray flux are essentially always accompanied by a large antiproton flux (see, e.g., [10,11]). We investigate what the antiproton fluxes would be in the same halo model, using model by model the same boost factors as are needed to fit the gamma-ray spectrum. We find that low-mass models (masses less than 100 GeV) that have low boost factors tend to overproduce antiprotons by a factor of around ten. Higher-mass models (above a few hundred GeV) have a lower antiproton rate, so the overproduction is slightly less. However, they give hardly any...
improvements to the fits to the gamma-ray spectrum. We will perform this analysis in a
general minimal supersymmetric standard model (MSSM), but as the correlation between
gamma rays and antiprotons is a general feature, our results will be more general. Our
conclusion is that the proposal of de Boer et al [2] for explaining the gamma excess in
all sky directions is, at present, not viable. However—we cannot exclude
the possibility of a small contribution to the diffuse gamma-ray flux from dark matter
annihilations.

2. Description of the model

Gamma rays have the advantage of pointing back directly to their sources in the Galaxy
and not suffering from energy losses. This, together with known gamma-ray spectral shape
from dark matter annihilation (distinct from the conventional background), permits us to
extract the sky-projected dark matter distribution from the EGRET observations. Taking
this one step further de Boer et al propose a specific dark matter profile, with 18 free
parameters, and do a best fit to the EGRET data (for details, see [2]). The density profile
de Boer et al obtain consists of a dark matter halo with the following ingredients:

• a triaxial smooth halo;
• an inner ring at about 4.15 kpc with a density falling off as $\rho \sim e^{-|z|/\sigma_{z,1}}; \sigma_{z,1} = 0.17$ kpc; and
• an outer ring at about 12.9 kpc with a density falling off as $\rho \sim e^{-|z|/\sigma_{z,2}}; \sigma_{z,2} = 1.7$ kpc;

where $z$ is the height above the galactic plane.

The triaxial halo is a modified isothermal sphere, but flattened in the direction of the
Earth and in the $z$-direction. The inner ring is rather broad, but located very close to
the baryonic disc, with an exponential fall-off above the galactic plane. The outer ring
is more massive and slightly narrower and also exhibits an exponential fall-off above the
galactic plane. The outer ring is also taken to have a sharper fall-off on the inside than
the outside. Both rings are elliptic. The details of the parametrization of the dark matter
model can be found in [2]. In figure 1, we show the strong concentration of dark matter
to the disc (upper panel) as well as the ring structure of the model (lower panel). The
steep exponential density fall-off away from the disc, originating from the two rings, can
be seen most clearly in the upper right plot.

Since conventional models of the diffuse gamma-ray emission employ scattering of
cosmic rays on gas and dust in the galactic disc, we may already note that this model will
produce a gamma-ray flux that has an angular distribution very similar to the generally
accepted cosmic ray contribution [13]. In fact, besides the need for measurements with
a better energy resolution such as will be given by GLAST, the desired spectral shape
can also be obtained by adjusting the balance between the contributions from proton
and electron cosmic rays (whose intensity is very poorly constrained away from the solar
neighbourhood) [13]. In [13] it was shown that one can get a good agreement with EGRET

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3 We note that earlier versions of the scenario of de Boer et al, e.g. [4], which had higher-mass models favoured,
did include a discussion of the antiproton fluxes. In the later papers with lower-mass models, they do not discuss
the issue. We furthermore conclude that in the earlier papers, where a NFW [12] dark matter profile was used,
the EGRET observations in all sky directions were not explained and, consequently, dark matter annihilations
could not alone explain all the gamma excess.
3. Astrophysical problems with the model

Even though the dark matter halo profile given by de Boer et al explains the EGRET data very well, we will here go through some of the astrophysical objections to this model. First, one may note that the model of the dark matter really is very close to the ‘standard’ model for the baryons of the Milky Way, containing a thin and a thick disc and a central bulge (see, e.g., [14]). Since the dark halo is much more massive than the baryonic one, one of the first things one should investigate is whether there is room to place as much unseen matter in the vicinity of the disc as de Boer et al do.
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Table 1. Measured local surface densities $\Sigma$, within heights $|z|$, compared to the amount of dark matter in the model of de Boer et al [2]. The amount of dark matter exceeds the allowed span for unidentified gravitational matter in the inner part of the galactic disc (i.e. around $z = 0$) [19, 17].

| Surface density | Dynamical | Identified | Unidentified | Dark matter in [2] |
|-----------------|-----------|------------|--------------|-------------------|
| $\Sigma_{50 \text{pc}}$ | $9-11$ | $\sim 9$ | $0-2$ | $4.5$ |
| $\Sigma_{350 \text{pc}}$ | $36-48$ | $\sim 34$ | $2-14$ | $19$ |
| $\Sigma_{800 \text{pc}}$ | $59-71$ | $\sim 46$ | $13-25$ | $29$ |
| $\Sigma_{1100 \text{pc}}$ | $58-80$ | $\sim 49$ | $9-32$ | $35$ |

3.1. Disc surface mass density

By observations of the dynamics and density fall-off of stars in the disc, one can get a measure of the gravitational pull perpendicular to the galactic plane. This in turn can be converted to an allowed disc surface mass density, a method pioneered by Bahcall [15]. Recent analyses [16]–[18] of the disc surface mass density at the solar system location have converged to a model with little room for a concentration of dark matter in the disc. Observations are well described by a smooth dark matter halo and a disc of identified matter (mainly containing stars, white and brown dwarfs and interstellar matter in form of cold and hot gases). Table 1 shows the observed local surface mass density in both identified components and the total dynamical mass within several heights. Their differences then give an estimate of the allowed amount of dark matter in the local disc—and the result is an exclusion of the possibility of such a strong concentration of unidentified/dark matter as is derived in [2]. All these estimates also agree well with the observed local density of $0.102 \pm 0.006 M_\odot/\text{pc}^2$ in dynamical mass and $0.092 M_\odot/\text{pc}^2$ in visible matter [19, 17]. This gives room for only about $0.01 M_\odot/\text{pc}^2$ in unidentified matter, which should be compared to the dark matter density of $0.05 M_\odot/\text{pc}^2$ in the model of de Boer et al [2].

From these numbers alone, the de Boer model gives a too high mass density. One should keep in mind, however, that the estimates of the possible amount of dark matter are somewhat uncertain and that the disc models also have uncertainties of the order of 10% in their star plus dwarf components and uncertainties as large as about 30% in their gas components. Also the de Boer et al model could easily be modified to give a lower disc surface mass density at the solar system’s location in the Galaxy. However, such a modification just to circumvent this problem seems fine-tuned. One should keep in mind that the model, as it now stands, already has made these modifications, e.g. the outer ring is Gaussian in shape in the radial direction, except that it is forced to zero relatively fast on the inside. This ad hoc cut-off lets the outer ring be very massive, while keeping the local density unaffected. In figure 1, the disc surface mass density for the halo model of de Boer et al is shown. We clearly see that in this model, the Earth is located in a region with relatively low disc mass surface density. Modifying the model to reduce this further would make the model even more fine-tuned. It is also not unlikely that, e.g., recent SDSS

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4 Even though the estimates are made under the assumption of a smooth dark matter halo these constraint still holds even for a wide range of varying dark matter profiles, including the profile concerned here [36].
The dark matter interpretation of the EGRET gamma excess [14] could put constraints on the halo model further away from the solar system, but such an analysis has, to our knowledge, not been performed yet.

To summarize, the de Boer model seems to be in slight conflict with the estimates of the disc surface mass density. It is certainly possible to modify their dark matter model to avoid exceeding the allowed local disc surface mass density, but the model would become even more fine-tuned with such a modification. In fact, the proposal made by de Boer et al to explain the gamma excess by introducing dark matter and avoid any fine-tuning of the electron and proton injection spectra, as in [13], actually ends up being considerably fine-tuned itself.

3.2. Ring profiles

The rings have an exponential fall-off above the galactic plane as given in section 2. Actually, the outer ring is claimed [2] to be consistent with an observed overdensity of stars, the Monoceros stream [20,21]. However, a recent analysis of Sloan Digital Sky Survey (SDSS) data [14] indicates that this is not really a ring but rather a localized structure like that expected from a merging dwarf galaxy with tidal arms, as already conjectured in [21]. In the original EGRET paper, this structure is clearly visible, but not as a ring (as it is not visible in quadrant IV in the notation of [5], figure 9).

In most models of cold dark matter, one would expect the dark matter distribution to be much more isotropic than that of the baryonic disc material, which supposedly forms dissipatively with energy loss but very little angular momentum loss [22]. In fact, we know of no reasonable example, from numerical simulations, that would indicate that the model shown in figure 1 resembles a dark matter halo.

4. Comparison with antiproton data

4.1. Calculating the antiproton fluxes

We will here investigate what antiproton fluxes, from annihilation in the dark matter halo, that the de Boer et al model would predict. To do this, we follow the approach of de Boer et al [2] as closely as possible and proceed as follows.

(1) We fit the expected background and signal to EGRET’s observed diffuse gamma flux towards the galactic centre, with the normalization of the background and signal as free parameters. We here use region A in [2], which is towards the galactic centre (±30° in longitude and ±5° in latitude from the galactic centre).

(2) From the best-fit signal normalization, we derive the required boost factor for the gamma flux from dark matter annihilation.

(3) Following de Boer et al, we assume that this boost factor is independent of location in the Galaxy (see the comment in section 4.4 below though).

(4) As the boost factor is assumed to be independent of location in the Galaxy, the same boost factor would apply also for the antiproton fluxes. We thus calculate the

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5 We note that in the analysis of de Boer et al they also subtract data in regions near the centre and the disc (see figure 3 in [2]) and then put it back as a signal with similar angular distribution. The only difference is the spectral shape, which is claimed to fit better a contribution from dark matter annihilation.
expected antiproton flux for the de Boer et al halo profile and then boost it by the same boost factor as is found from the EGRET fit.

For the background gamma flux, we have used both the standard background (as given in figure 2 of [2]) and the optimized background (as given in figure 6 of [2]). The difference between these are that the optimized background has a modified proton and electron injection spectrum, trying to give a good description of the EGRET data without dark matter. Both these models are based upon models given by Strong et al [13].

The differential gamma-ray flux in a given direction is given by

$$\Phi_\gamma = 9.35 \times 10^{-10} \left( \frac{dN_\gamma}{dE_\gamma} \right) \frac{\sigma v}{10^{-29} \text{ cm}^3 \text{ s}^{-1}} \left( \frac{\text{GeV}}{m_\chi} \right)^2 J(\theta, \phi) \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$$

with

$$J(\theta, \phi) = \frac{1}{8.5 \text{ kpc}} \int_{\text{line of sight}} \left( \frac{\rho(\theta, \phi, l)}{0.3 \text{ GeV cm}^{-3}} \right)^2 \text{ dl.}$$

Averaging this over region A towards the galactic centre, we find that $\langle J \rangle = 123.3$.

For the signal, we use DarkSUSY [23] to calculate the dark matter annihilation cross sections and gamma-ray yields. We then use the equations above to calculate the flux in region A. Following de Boer et al, we calculate the flux in eight EGRET bins from 0.07 to 10 GeV. We have done this for a set of rather general MSSM models, where we have varied the standard MSSM parameters ($\mu$, $M_2$, $m_0$, $\tan \beta$, $A_t$, $A_b$ and $m_A$) between very generous bounds (up to several TeV for the mass parameters). We have only kept models that do not violate any accelerator constraints and that have a relic density in the WMAP preferred range $0.104 \leq \Omega h^2 \leq 0.121$. We have about 100 000 models satisfying these constraints (but make the plots with binned results as the density of points has no physical meaning).

In figure 2(a) we show the boost factors of the signal that gives the best fits. We see that we roughly agree with the results in [1] that the required boost factors are of order 10 or more. We have also calculated the boost factors needed when we use the so called optimized background in our fits. We here also get roughly the same result as in [2], i.e. the required boost factors are about a factor of 3–4 lower.

In figure 2(b), we show the $\chi^2$ of the fits (divide by $8 - 2 = 6$ to get the reduced $\chi^2$). As already shown by de Boer, it is possible to get very good fits for masses below about 100 GeV. We also note that the fits with the optimized background are never as good as with the standard background. On the other hand, the fits are not as bad for higher masses, as there is less need for a signal in this model. One should note that we use relative errors of only 7% for the gamma fluxes, although the overall uncertainty is often quoted to be 10–15% [24,13]. The reason for using smaller errors is to take into account the fact that the relative point-to-point errors are expected to be less than the overall normalization error, dominated by systematics. The overall normalization uncertainty is irrelevant here, since in the fitting the normalization is a free parameter anyway. We follow de Boer et al and use their estimate of 7% for the relative errors in our $\chi^2$ fits. We note that our results are not sensitive to this choice though (apart from the actual $\chi^2$ values of course).
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Figure 2. (a) The boost factor needed for a good fit of background and a dark matter signal to the EGRET data in region A. (b) The $\chi^2$ of the fits ($8 - 2 = 6$ degrees of freedom).

4.2. Comparing with BESS data

We are then ready to compare with antiproton measurements. We use DarkSUSY [23] to calculate the antiproton fluxes for each of these MSSM models and with the halo profile of de Boer et al. As our calculation assumes an axisymmetric halo profile, we symmetrized the de Boer et al profile in such a way that we, for any given radius $r$, take an average of the source function ($\sim \rho^2$) over the azimuthal angles. We do not expect this to introduce any large errors as the antiproton diffusion effectively smears out local variations in the density. In fact, from the variations of the density over the azimuthal angles, we do not expect this symmetrization to introduce larger errors than at most a factor of 1.5.

We have chosen to primarily compare with BESS (Balloon-borne Experiment with a Superconducting Spectrometer) data from 1998 [25], where we have chosen the bin at 0.40–0.56 GeV. The reason we choose the BESS 98 data is that for these data the solar modulation parameter is relatively low ($\phi_F = 610$ MV) and the reason we choose a low-energy bin is that here the signal is expected to be relatively high compared to the background.

Applying the same boost factors for the antiproton fluxes as obtained from the fit to EGRET data we show in figure 3(a) the expected antiproton flux from both the fit with the standard background and the fit with the optimized background. The models with low masses, that have low $\chi^2$, clearly overproduce antiprotons by a large amount. In figure 3(b) we show (for the standard background) the antiproton flux, but coded with $\chi^2$. We have here also chosen to impose a cut on the boost factor, to only allow models with reasonably low boost factors. To be conservative, we have allowed the boost factor to be as high as 100, which is higher than expected from recent analyses (see e.g. [26, 27]). It is fairly evident that all the models with good fits to the EGRET data give far too high antiproton fluxes.

We have also compared with a set of mSUGRA rates (the same ones used in [28]). The mSUGRA models show the same general pattern as the MSSM models (i.e. similar
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Figure 3. The antiproton fluxes boosted with the same boost factor as found for the gamma rays. In the left panel, the antiproton fluxes for both standard and optimized background are shown, whereas in the right panel, the $\chi^2$ of the fits has been indicated ($8 - 2 = 6$ dof). In the right panel, we also indicate with a solid line how far down we could shift the models by choosing an extreme minimal propagation model (see section 4.3).

Other dark matter candidates, like Kaluza–Klein (KK) dark matter, would also give similar behaviour since the gamma rays and antiprotons are so correlated. However, for, e.g., KK dark matter from Universal Extra Dimensions [29] we would not improve the fits to EGRET data as only heavier models are favoured by the relic density constraint.

4.3. Antiproton propagation uncertainties

Of course, it is a well-known fact that the antiproton flux from dark matter annihilations is beset with large uncertainties relating to unknown diffusion parameters combined with uncertainties in the halo distribution. As an example, in [30] it is pointed out that the estimated flux may vary by almost a factor 10 up or down for models that predict the measured B/C ratio (i.e., the relation between secondary and primary cosmic rays) within the uncertainties.

Hence, it might seem that the models producing too many antiprotons in figure 3 are not really excluded if the uncertainties of the antiproton propagation are included. However, the results of a factor of around 50 uncertainty in [30] are only valid for a relatively smooth halo profile, so we need to investigate this in some more detail for the de Boer et al profile. To do that, we will recalculate the antiproton fluxes with the propagation code in [30] and with propagation parameters chosen to be as extreme as we can allow from other cosmic ray data (mainly B/C).
Table 2. Astrophysical parameters of the cosmic ray galactic propagation models giving the maximal, median and minimal primary antiproton fluxes compatible with B/C analysis [30]. $\delta$ is the exponent for the diffusion coefficient’s rigidity dependence, $K_0$ is the normalization of the diffusion coefficient, $L$ is the half-height of the diffusion box, $V_c$ is the galactic wind and $V_a$ is the reacceleration velocity (see [30] for more details).

| Case | $\delta$ (kpc$^2$/Myr) | $K_0$ (kpc) | $V_c$ (km s$^{-1}$) | $V_a$ (km s$^{-1}$) |
|------|-------------------------|------------|---------------------|---------------------|
| Max. | 0.46 | 0.0765 | 15 | 5 | 117.6 |
| Med. | 0.70 | 0.0112 | 4 | 12 | 52.9 |
| Min. | 0.85 | 0.0016 | 1 | 13.5 | 22.4 |

The main reason for the large uncertainties found in [30] is a degeneracy (for the secondary signal) between the height of the diffusion box and the diffusion parameter. If we increase the height of the diffusion box, we would get a larger secondary signal because cosmic rays can propagate longer in the diffusion box before escaping. This can be counterbalanced by increasing the diffusion coefficient to make the cosmic rays diffuse away faster from the galactic disc. Hence, for the secondary signal, which originates in the galactic disc, we can get acceptable fits by changing these parameters. For the dark matter signal though, the effect of these changes is different. If we increase the height of the diffusion box, we also increase the volume in which annihilations occur, and the total flux increases more than is counterbalanced by an increase in the diffusion coefficient. In [30] they then found that for a NFW (or isothermal) profile, the different acceptable configurations of diffusion height and diffusion coefficient would cause an increase/decrease of up to a factor of 10 compared to the median value.

Let us now focus on the de Boer et al profile. The most important parts for the antiproton signal are the rings that decay exponentially with the height above the galactic plane. Hence, this source distribution is much more concentrated into the galactic disc than a smooth halo profile is. We therefore expect a more modest change of the fluxes with the extreme values of the diffusion parameters than found in [30]. As a complement to our calculations with DarkSUSY, we have derived the antiproton fluxes in the de Boer model for the extreme diffusion parameters given in [30] and which we recall in table 2. This calculation has been done with the propagation code in [30].

For illustration, we show in figure 4 the full yield of primary antiprotons for a selected supersymmetric configuration for which the agreement with the EGRET data is very good—$\chi^2$ of order 3 (neutralino mass of 50.1 GeV and derived boost factor of 69). For the sake of completeness, we have taken into account tertiary antiprotons as in [31] and computed the effect of diffusive reacceleration with the help of the same Crank–Nicholson scheme as in [32]. Solar modulation has been modelled with the simple force–field approximation where a Fisk parameter of $\phi_F = 610$ MV has been assumed. The red solid curve in figure 4 corresponds to the median cosmic ray configuration of table 2. The yellow band is delimited by the extreme configurations and gives an indication on how well the flux of neutralino induced antiprotons can be derived in the case of the de Boer et al dark matter distribution. For the maximal cosmic ray model, we observe an increase in the antiproton flux by a factor of 2.5 whereas for the minimal configuration, we find...
A supersymmetric model that provides a good fit to the EGRET data has been selected and its antiproton yield has been carefully derived. It is shown by the red solid line in the case of the median cosmic ray configuration of table 2. Predictions spread over the yellow band as the cosmic ray propagation parameters are varied from the minimal to maximal configurations. The long-dashed black curve is calculated with DarkSUSY for a standard set of propagation parameters (see [28] for details). The narrow green band stands for the secondary component. As is evident from this figure, the antiproton fluxes for this example model clearly overshoot the data.

Figure 4. A supersymmetric model that provides a good fit to the EGRET data has been selected and its antiproton yield has been carefully derived. It is shown by the red solid line in the case of the median cosmic ray configuration of table 2. Predictions spread over the yellow band as the cosmic ray propagation parameters are varied from the minimal to maximal configurations. The long-dashed black curve is calculated with DarkSUSY for a standard set of propagation parameters (see [28] for details). The narrow green band stands for the secondary component. As is evident from this figure, the antiproton fluxes for this example model clearly overshoot the data.

a decrease of a factor of 2.6—both at energies lying between 0.4 and 0.6 GeV. The total width corresponds therefore to an overall factor of ~6.5 to be compared to a factor of ~50 in the case of an NFW dark matter halo. As expected, the uncertainties are much smaller in the de Boer et al model compared to the more conventional halo profile. Again, the main reason for this is that the dark matter in the de Boer model is located much closer to the galactic plane and its distribution is reminiscent of the gaseous disc of the Milky Way that is responsible for the conventional secondary background. The latter is featured in figure 4 as the narrow green band that has been derived in [32] from the observed B/C ratio. From this calculation we also get an estimate of the possible uncertainties arising from different propagation codes. In figure 4, the long-dashed black curve has been computed with the DarkSUSY package using a typical cosmic ray propagation (as described in [28]). Because diffusive reacceleration has not been implemented in that case, the flux falls more steeply close the neutralino mass. Notice however that it is fairly similar to the red solid line, calculated with the propagation code in [30]. We can therefore conclude that diffusive reacceleration does not substantially modify the shape of the antiproton spectrum—especially in the energy range of interest. We also note that the two different propagation codes, DarkSUSY and the code of [30], give very good
agreement and should not yield any additional theoretical error. Notice finally that the primary yellow uncertainty band is at least an order of magnitude above the secondary green component. The latter alone can already account for the antiproton observations as is clear in figure 4. We conclude that the supersymmetric model that has been selected here because it provides a good fit to the EGRET excess should be excluded as it by far overproduces antiprotons. In figure 4 we also compare with the BESS data at energies other than our previously selected energy bin. It should be evident from the figure that the model overproduces antiprotons at essentially every measured energy.

We have here compared with one example model, but this argument can be made more general. In figure 3(b) we show with a solid line how far down we could shift the models down by going to the extreme minimal model. As can be seen, the antiprotons are still overproduced by a factor of 2–10 for the models with good fits to EGRET data. It is therefore difficult to see how the dark matter interpretation of the EGRET data could be compatible with the antiproton measurements.

4.4. Other antiproton uncertainties

Above we mentioned the antiproton uncertainties coming from our lack of knowledge of the propagation model. We also have uncertainties arising from the assumptions in the approach of de Boer et al. For example, the boost factor is assumed to be independent of position in the Galaxy. This is probably not a very well-justified assumption as we would expect the boost factor to depend on the formation history of that particular region in the Galaxy. If the boost factors do depend on the position in the Galaxy, then the boost factors for the flux at reception at Earth can be different for gamma rays and antiprotons since the signal in general come from different parts of the Galaxy (the gamma signal can e.g. be dominated by annihilation at the galactic centre, whereas the antiprotons could come from a more nearby structure). We will here investigate what the uncertainties on the boost of the antiproton flux as seen at the Earth could be if we relax the assumption of space independent boost factors.

In particular, galactic tidal interactions should destroy clumps [33] in the inner (older) parts of the Milky Way and especially in the inner ring, which is the most prominent feature in the de Boer model when it comes to the fits to the gamma-ray fluxes. On the other hand, the antiprotons that are detected at the Earth originate from a broad region of the Milky Way halo. A significant portion is produced in the inner ring, but a substantial part comes also from the outskirts where clumps have survived. The correct effective boost factor which should have been implemented in the antiproton calculations should therefore probably be larger than the value derived from assuming a spatially constant boost factor.

We can quantify these uncertainties though. If we take away the inner ring, the antiproton fluxes goes down a factor of 2.0. If we take away the outer ring, the antiproton fluxes go down by a factor of 1.4. And, finally, if we take away the smooth triaxial halo, the antiproton fluxes go down by a factor of 2.2. Hence, we can conclude that the antiproton fluxes at the Earth are dominated by annihilation in the inner ring and the smooth triaxial halo. Since the antiprotons coming from the inner ring originate in the same place as the gamma rays that dominate the flux in region A, the boost factor derived from the gamma flux should be very close to the effective boost factor for these antiprotons. As noted
above, this makes up half of the antiproton flux at Earth. For the other half, coming mostly from the triaxial smooth halo, our use of the same effective boost factor as derived from gamma rays from region A is most likely not correct. However, as noted above, we would expect the boost factor to be larger in these less dense regions, so our (and de Boer’s) assumption of space independent boost factors would lead to an underestimate of the antiproton flux.

Another argument—slightly more technical—points in the same direction. The local boost factor $B_c$ of a clump of mass $M_c$ is defined [34] with respect to some value of reference $\rho_0$ through the relation

$$\int_{\text{clump}} d^3\vec{x} \delta \rho^2 (\vec{x}) = \rho_0 M_c B_c,$$

(3)

where $\delta \rho$ is the dark matter density inside the substructure. If large boost factors are needed to explain the EGRET data, this means that the dark matter is tightly packed even inside the inner ring. That region is already fairly dense with a density of reference $\rho_0 = 4.5$ GeV cm$^{-3}$. In contrast, antiprotons originate from a larger domain where the neutralino density is certainly smaller on average than inside the inner ring. If the clumps have basically the same mass and density profile all over the Milky Way halo—which is probably correct in the case where very small substructures dominate, as they should have survived the galactic tides—the product $\rho_0 B_c$ remains constant. We are forced to the conclusion that the actual effective boost value which should be used for antiprotons is once again larger than in the case of the EGRET data. Therefore assuming identical effective boost factors (as seen at Earth) for the photon and antiproton flux is very conservative. The lower antiproton limit featured in figure 3(b) should actually be shifted upwards, even further above the BESS 98 stripes.

5. Comparison with direct detection

With the enhanced dark matter densities in the de Boer et al model one may wonder whether these models would not have been seen already in direct detection experiments. To make a simple estimate of this, we plot the cross section of scattering on protons versus mass in figure 5. We compare with the latest CDMS results [35], but since those results apply for a local dark matter density of 0.3 GeV cm$^{-3}$, we have rescaled the limits with the local density in the de Boer et al model. To be more specific, we have lowered the limits by $\rho_{\text{Boer}}/\rho_0 = 1.93/0.3$, which is the ratio of the local dark matter density in the de Boer et al model and a ‘standard’ halo model. As can be seen, most models would seem to be excluded by the latest CDMS results [35]. However, in deriving these limits, a standard Gaussian velocity distribution has been assumed. This is most probably a reasonable approximation for the triaxial halo in the de Boer et al model, but most of the local density comes from the inner ring, where not much is known about the velocity. If the inner ring were to rotate along with the Galaxy, we would expect lower rates than indicated in the figure since the relative velocity between the dark matter and us would be lower. However, if it counter-rotates, we would expect even higher rates. If we were to be conservative and assume that the inner ring would produce no significant rates in direct detection experiments, the limits from CDMS would be reduced by a factor of 0.5/0.3 (as the local density from the smooth halo is 0.5 GeV cm$^{-3}$ in the de Boer et al model). In
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Excluded CDMS 2004
Excluded, no inner ring
\[ \chi^2 < 10 \]
\[ \chi^2 < 25 \]
\[ \chi^2 < 60 \]
\[ \text{Boost factors} < 100 \]
Neutralino mass (GeV)
\[ \sigma_p \ (\text{pb}) \]
\[ 10^{-5} \]
\[ 10^{-6} \]
\[ 10^{-7} \]
\[ 10^{-8} \]
\[ 10^{-9} \]
\[ 10^{-10} \]
\[ 10^{-11} \]
\[ 10^{-12} \]
\[ 10^{-13} \]

Figure 5. The spin independent cross section for direct detection versus mass is shown for models with boost factors below 100. The \( \chi^2 \) of the fits has been indicated with different symbols. The CDMS limits [35] have been lowered by a factor of \( \rho_{\text{Boer}} / \rho_0 = 1.93/0.3 \) as the density in the de Boer is higher than assumed in the analysis of [35]. Also indicated is the limit in the case where the inner ring would not contribute to the direct detection rates (reduced by factor of 0.5/0.3 compared to [35]).

figure 5 we indicate this exclusion limit with a dashed line. As can be seen, some of the models would then fall below the exclusion limit, but some would still be above.

Hence, one can conclude that the de Boer et al models produce significant rates in direct detection experiments, and some of the good models are already excluded even if uncertainties of the velocity distributions are taken into account. However, we cannot exclude all of the good models, due to these uncertainties, but many of the models giving the best fits are well within reach with future improved direct detection experiments.

6. Discussion

We have here investigated the idea put forward by de Boer et al that the observed EGRET excess of diffuse gamma rays could be due to dark matter annihilation in the Milky Way. This is an interesting idea, but as far as we can see the model does not seem very plausible when other constraints are taken into account. The strongest constraint is probably the antiproton flux, which would be overproduced far above the flux measured by BESS. Even if the uncertainties of the antiproton flux are included, the antiproton flux is still more than a factor of 2–10 above the BESS measurements. From the analysis in this paper one also finds (see figure 3(b)) that models that would be compatible with the antiproton data would always have very bad fits to the EGRET data (reduced \( \chi^2 > 60/6 \)). Actually, the
optimized background model in [13] would produce a much better fit (reduced $\chi^2 \sim 22/6$; which can also be read of at the high-mass end in figure 2(b), where the signal does not contribute much to the fits). Hence, the models with acceptable antiproton fluxes are not very interesting as they give worse fits to the gamma excess than the more conventional models.

Other objections to the model come from astrophysics. For example, the density in the disc in the de Boer model is a little bit too high to be compatible with stellar motions in the solar neighbourhood. This could of course be circumvented by adjusting the densities in the de Boer et al model to have a dip at our location in the solar system. Such fine-tunings are not very appealing though, especially as the model already has a local minimum at the solar neighbourhood. One has to be careful interpreting these results on the disc surface density though as there are large uncertainties and model dependences. To be conservative, we interpret these too high disc surface mass densities as a hint of problems with the model. The actual density profiles of the rings (exponential fall-off away from the disc) are also not what you expect from dark matter. In fact, we believe that the de Boer et al model is most likely a fit of the baryonic matter distribution of the Galaxy, and not the dark matter density. One could also wonder whether the background models could be improved further and provide an even better fit to the EGRET data. In fact, the optimized background model in [13] already gives a good fit to the EGRET data—especially when conventional/larger uncertainties of $\sim 15\%$ for EGRET’s observed gamma fluxes are adopted (reduced $\chi^2 \sim 5/6$). This optimized model was accomplished by tuning the electron and proton injection spectrum without violating any of the cosmic ray constraints, such as B/C. Hence, there is no real need for dark matter to explain the EGRET data. New experiments are on their way though with GLAST flying in 2007 and with new and better data, we will one hopes get a better understanding of the gamma-ray sky and whether there are any (clear) signals of dark matter out there.

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