Uncertainties of the antiproton flux from Dark Matter annihilation in comparison to the EGRET excess of diffuse gamma rays

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Abstract. The EGRET excess of diffuse Galactic gamma rays shows all the features expected from dark matter annihilation (DMA): a spectral shape given by the fragmentation of mono-energetic quarks, which is the same in all sky directions and an intensity distribution of the excess expected from a standard dark matter halo, predicted by the rotation curve. From the EGRET excess one can predict the flux of antiprotons from DMA. However, how many antiprotons arrive at the detector strongly depends on the propagation model. The conventional isotropic propagation models trap the antiprotons in the Galaxy leading to a local antiproton flux far above the observed flux. According to Bergström et. al this excludes the DMA interpretation of the EGRET excess. Here it is shown that more realistic anisotropic propagation models, in which most antiprotons escape by fast transport in the z-direction, are consistent with the B/C ratio, the antiproton flux and the EGRET excess from DMA.

1 Introduction

The interpretation of the observed EGRET excess of diffuse Galactic gamma rays as Dark Matter annihilation (DMA) (see [1] or contributions by W. de Boer, C. Sander and M. Weber, this volume) could be a first hint at the nature of dark matter. The excess was observed in all sky directions. From the spectral shape of the excess the WIMP mass was constrained to be between 50 and 100 GeV and from the distribution of the excess in the sky the Dark Matter (DM) halo profile was obtained. One of the most important criticisms of this analysis was a paper by Bergström et. al. [2] claiming that the antiproton flux from DMA would be an order of magnitude higher than the observed antiproton flux. They used a conventional propagation model assuming the propagation of charged particles to be the same in the halo and the disk. However, the propagation in the halo (perpendicular to the disk) can be much faster than the propagation in the disk [3].

In this paper we show that the local antiproton flux from DMA can be strongly reduced in an anisotropic propagation model and that the DMA interpretation of the EGRET excess can by no means be excluded by Galactic antiprotons. In section 2 we discuss the problems of the isotropic model for cosmic ray transport leading to the fact that our galaxy can work as a large storage box for antiprotons. An anisotropic propagation model, which simultaneously describes the EGRET excess and the observed local fluxes of charged cosmic rays is introduced in section 3. Section 4 summarizes the results.

2 Antiproton flux in an isotropic propagation model

In order to explain the observed isotropy of Cosmic Ray (CR) fluxes one assumes the CRs to perform a random walk in all directions by scattering on randomly oriented turbulent magnetic fields inside the plasma. In this case the propagation is governed by a diffusion equation, which can be solved for the steady state case numerically. From the ratio of unstable/stable nuclei (like $^{10}\text{Be}/^{9}\text{Be}$) one obtains the average residence time of CRs in the Galaxy to be of the order of $10^7$ yrs. Particles can be lost either by fragmentation, decay or just leaving the Galaxy to outer space. Since they travel with relativistic speed the long residence time requires that they cannot move rectilinear to outer space, but must be scattering many times without loosing too much energy. During their journey CRs may interact with the gas in the Galaxy and produce secondary particles. The ratio of secondary/primary particles, like the B/C ratio is a measure for the amount of traversed matter (grammage) by CRs during their lifetime $t_{CR}$. The grammage is given by $\rho c t_{CR}$, where $c t_{CR}$ is the path length for a particle traveling with the speed of light $c$. It was found to be of the order of $10g/cm^2$ [4], which corresponds to a density of about 0.2 atoms/cm$^3$. This is significantly lower than the averaged density of the disk of 1 atom/cm$^3$, which suggests that CRs travel a large
time in low density regions. In an isotropic propagation model this would be the thin halo. However, as we will see in section 3 this interpretation is strongly model dependent.

An excellent program providing a numerical solution to the diffusion equation for CRs is the publicly available GALPROP code \[6, 7\]. The standard model for isotropic CR transport in GALPROP does not explain the EGRET excess of diffuse gamma rays. This could be remedied partially by applying strong breaks to the injection spectra of protons and electrons in order to obtain a higher intensity of protons and electrons above a few GeV, but the intensity below this break had to stay the same in order not to modify the gamma ray spectrum below 1 GeV \[8\]. These breaks are only applied for the electrons and protons, not for the other nuclei in order not to upset the B/C ratio. Different breaks in the injection spectra for different nuclei implies different acceleration histories for different nuclei. In addition, assuming the locally observed spectrum to be different from the spectra elsewhere in the Galaxy is unexpected, since diffusion is fast compared to the energy loss time, so diffusion equalizes the spectrum everywhere in agreement with the observation that the gamma ray spectra in all directions can be described by the same CR spectrum. If one attributes the EGRET excess to a new source, like DMA, one runs into the problem of a too large flux of antiprotons, as discussed in detail in \[2\]. We have implemented the DMA as a source term into the publicly available GALPROP code \[6, 7\] and find a similar result, as shown in Fig. 1a. This is not surprising, since GALPROP uses the same priors as the program used by \[2\]: (i) the propagation is dominated by diffuse scattering, which is assumed to be the same in the halo and the disk (ii) the gas in the disk is smoothly distributed (iii) the influence of the observed static magnetic fields can be neglected. The main reason for the large flux of antiprotons from DMA in such a model is the long residence time of charged particles \((10^7 \text{ yrs})\), which requires all particles to spend most of their lifetime in the thin galactic halo and enter and exit the dense galactic disk multiple times thus acquiring grammage. In this case antiprotons from DMA are trapped in the Galactic halo, just like conventional CRs, and DMA increases the averaged density of antiprotons by orders of magnitude, so the flux of antiprotons becomes of the same order of magnitude as the EGRET excess. Note that the production ratio of antiprotons/gammas from DMA is only at the percent level, as is well known from accelerator experiments for the fragmentation of mono-energetic quarks, so the enhancement of antiprotons comes from the propagation model, not from the production.

3 Antiproton fluxes in an anisotropic propagation model

The propagation picture with isotropic propagation is based on hydromagnetic wave theories, in which the random (small-scale) component of the magnetic fields dominates over or are of the same order of magnitude as the regular large scale components. From the isotropy of the CRs one assumes that the regular components of the magnetic fields can be neglected, so there is no preferred direction for Alfvén waves. The turbulent component is locally as large as \(10 \mu G\), while the regular field is only about \(3 \mu G\) \[9, 10\]. However, even if the turbulent small scale and regular large scale components are of the same order of magnitude the ratio of perpendicular/parallel diffusion is about 0.1 (see \[3\] and references therein), which implies that the CRs still preferentially follow the regular magnetic field lines, as demonstrated by following the trajectories of CRs in models of the Galactic magnetic fields \[11, 12\]. The regular component has strongly preferred directions: in the disk it is toroidal with a maximum
at about 150 pc above and below the disk and with an additional poloidal field with its maximum in the centre of the Galaxy. For fast parallel diffusion this implies that CRs preferentially move along the spiral fields just above or below the disk or they follow the poloidal component into the halo. An additional effect concerning charged particles may be related to molecular clouds: the gas density in the disk varies from $10^{-3}/\text{cm}^3$ in the warm ionized medium to $10^2/\text{cm}^3$ in clumps of cold gas with a size of a few pc. In the center the density may be as high as $10^7/\text{cm}^3$ in dense molecular clouds (MCs), where star formation occurs. On average the gas density is $1/\text{cm}^3$ in the disk. Inside MCs magnetic fields far above the random components have been observed (see [9] for a review). What is more important, these fields seem to be correlated with the observed static magnetic fields outside the MCs [13]. This can only be understood, if the MCs remember the large scale magnetic fields in the interstellar medium, i.e. if during the contraction flux freezing occurs. In this case the magnetic field lines from the ISM will become highly concentrated near the MCc and the MCs will form a network of interconnected clouds, focussing the magnetic field lines towards them. CRs in the ISM following these field lines will be reflected by the concentration of the field lines. As worked out by Chandran [14], the MCs can act as magnetic mirrors for CRs, just like the concentration of magnetic field lines near the poles from the earth trap the CRs in the famous Van Allen radiation belts. The large distances (pc scale) between the MCs allows to trap particles up to the TeV scale, thus increasing the grammage and the residence time. In such a setup particles acquire grammage and age in the low density regions in the disk (between MCs) and not in the halo as in the isotropic propagation model. Thus, the halo size is not a sensitive parameter anymore and particles, once in the halo, will be preferentially transported away from the disk by a combination of convection and fast diffusion along the regular poloidal field lines in the halo. We have implemented this propagation picture in the publicly available source code of GALPROP by (i) allowing for a diffusion tensor instead of a diffusion constant; (ii) allowing an inhomogeneous grid in order to have step sizes below 100 pc in the disk region and large step sizes in the halo; (iii) implementing the dark matter annihilation as a source term of stable primary particles, especially antiprotons, positrons and gamma rays, in the diffusion equation. The dark matter distribution was taken to be the one obtained from the EGRET excess [1]. The grammage and escape time were adjusted for charged particles to account for the fact that secondary particles are now produced largely locally, since particles produced far away from the solar system are likely to diffuse into the halo, thus escaping to outer space. If the trapping in MCs is effective, one would expect it to increase the grammage and residence time by the same factor, called grammage parameter $c$. Since the trapping mechanism is independent of energy and only depends on the pitch angle the trapping can be modeled by a

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**Fig. 2.** The B/C ration (a) and the beryllium-fraction (b) for an anisotropic diffusion model with trapping between MCs (red) and for a model with isotropic diffusion (green).

| Name                        | Symbol      | value          |
|-----------------------------|-------------|----------------|
| Diffusion in x, y           | $D_{xx}, D_{yy}$ | $5.8 \cdot 10^{20} \text{cm}^2/\text{s}$ |
| Diffusion in z              | $D_z$       | $3.0 \cdot 10^{19} \text{cm}^2/\text{s}$ |
| break rigidity              | $\rho_0$   | $4.0 \cdot 10^5 \text{MV}$ |
| energy dependence           | $\alpha$ for $\rho < \rho_0$ | $0.33$ |
|                             | $\alpha$ for $\rho > \rho_0$ | $0.6$ |
| Convective velocity         | $V_0$       | $250 \text{kms}^{-1}$ |
| Convective slope            | $\frac{dV}{dz}$ | $37 \text{kms}^{-1} \text{kpc}^{-1}$ |
| grammage parameter          | $c$         | $12$ |

**Table 1.** Parameters of an anisotropic propagation model. The components off the diffusion tensor are given by $d_{xx}(\rho) = \beta \cdot D_z(\rho)^{-1}$, convection is given by $V(z) = V_0 \cdot \theta(z - 0.1 \text{ kpc}) + \frac{dV}{dz} z$. Note that this set of parameters is not unique, since they are all correlated.
constant c. The most important GALPROP parameters have been summarized in Table 1. The transport from the disk to the halo is quite uncertain, since the magnetic field lines have to be continuous, which implies they must connect from the toroidal field to the halo. It should be noted that the average scale height of SN1a is expected to be about 350 pc (thick disk) and the ejecta connect to the halo in chimney like structures (see e.g. [15] and references therein), which can drive magnetic field lines towards high altitudes (≈ 1 kpc), thus facilitating the transport to the halo by the fast parallel diffusion. This was simulated as an enhanced convection term starting at \( V_0 = 250 \text{km/s} \) at 100 pc above the disk and then increasing with the distance \( z \) above the disk as \( dV/dz = 37 \text{km/s/kpc} \). It should be mentioned that this set of parameters is not unique, since they are all correlated. As shown in Figs. 1D and 2 the B/C ratio, the \(^{10}\text{Be}/^{9}\text{Be} \) ratio and the antiproton flux are all well described by this set of parameters. Note that most of the antiprotons from DMA in the halo diffuse into outer space and are never observed in the detector in contrast to the diffusion model with isotropic diffusion (Fig. 1b). It should also be noted that the antiprotons produced in the ring-like structures of DM near us are unlikely to reach us, since they follow the toroidal magnetic field lines, so they diffuse fast in the \( \phi \) coordinate, not in \( r \). Such a propagation would require tuning the 3D version of GALPROP. However, this takes an excessive amount of CPU time and memory and will be subject of future studies. It should be kept in mind that the convection speed and the diffusion coefficient in the \( z \) direction are not unique. Both processes simply take care of the enhanced propagation in the \( z \)-direction, thus reducing drastically the acceptance of charged particles from DMA in the halo. As a result, the statement that the DMA interpretation of the EGRET is “excluded by a large margin” because of the overproduction of antiprotons, as claimed by [2] is only valid within a propagation model based on isotropic propagation. Models with different propagation in the halo and the disk can perfectly describe all observations including DMA.

4 Conclusion

Tracing of charged particles in realistic models of the regular Galactic magnetic fields with a turbulent (small-scale) component has shown that CRs remember the regular field lines, even if the irregular component is of the same order of magnitude as the regular, thus leading to enhanced diffusion in \( \phi \) and \( z \) (see Fig. A1 in [11]). With such an anisotropic propagation model the amount of antiprotons expected from DMA can be reduced by one to two orders of magnitude. Therefore the claim by [2] that the DMA interpretation of the EGRET excess of diffuse Galactic gamma rays is excluded is strongly propagation model dependent. It only applies to a propagation model with isotropic diffusion. An anisotropic propagation model with different propagation in the halo and the disk can reconcile the EGRET excess with the antiproton flux and the ratios of secondary/primary and unstable/stable nuclei. Clearly the DMA search for light DM particles is propagation model dependent.

Taking these uncertainties into account shows that DMA is a viable explanation of the EGRET excess of diffuse Galactic gamma rays, as shown in [1] and can by no means be excluded by the antiproton flux predicted by a specific model.

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