Is the Dark Matter interpretation of the EGRET gamma ray excess compatible with antiproton measurements?

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The diffuse galactic EGRET gamma ray data show a clear excess for energies above 1 GeV in comparison with the expectations from conventional galactic models. This excess shows all the features expected from Dark Matter WIMP Annihilation: a) it is present and has the same spectrum in all sky directions, not just in the galactic plane, as expected for WIMP annihilation b) it shows an interesting substructure in the form of a doughnut shaped ring at 14 kpc from the centre of the galaxy, where a ring of stars indicated the probable infall of a dwarf galaxy. From the spectral shape of the excess the WIMP mass is estimated to be between 50 and 100 GeV, while from the intensity the halo profile is reconstructed, which is shown to explain the peculiar change of slope in the rotation curve at about 11 kpc (due to the ring of DM at 14 kpc).

Recently it was claimed by Bergström et al. that the DM interpretation of the EGRET gamma ray excess is excluded by the antiproton fluxes, since in their propagation model with isotropic diffusion the flux of antiprotons would be far beyond the observed flux. However, the propagation can be largely anisotropic, because of the convection of particles perpendicular to the disc and inhomogeneities in the local environment. It is shown that anisotropic propagation can reduce the antiproton yield by an order of magnitude, while still being consistent with the B/C ratio. Therefore it is hard to use antiprotons to search for light DM particles, which yield a similar antiproton spectrum as the background, but the antiprotons are a perfect means to tune the many degenerate parameters in the propagation models.

1. Introduction

Cold Dark Matter (CDM) makes up 23% of the energy of the universe, as deduced from the WMAP measurements of the temperature anisotropies in the Cosmic Microwave Background, in combination with data on the Hubble expansion and the density fluctuations in the universe. The nature of the CDM is unknown, but one of the most popular explanation for
it is the neutralino, a stable neutral particle predicted by Supersymmetry.\textsuperscript{2} The neutralinos are spin 1/2 Majorana particles, which can annihilate into pairs of Standard Model (SM) particles. The stable decay and fragmentation products are neutrinos, photons, protons, antiprotons, electrons and positrons. From these, the protons and electrons disappear in the sea of many matter particles in the universe, but the photons and antimatter particles may be detectable above the background, generated by particle interactions. Searches for the stable products of dark matter annihilation (DMA) (so-called indirect Dark Matter detection) have been actively pursued, see e.g the review by Bergström\textsuperscript{3} or more recently by Bertone, Hooper and Silk.\textsuperscript{4}

In previous papers we showed that the so-called EGRET excess of diffuse galactic gamma rays\textsuperscript{5} exhibits all the features of DMA.\textsuperscript{6-8} However, Bergström et al.\textsuperscript{9} claimed that the DM interpretation of the EGRET gamma ray excess is incompatible with the antiproton fluxes, since in their propagation model with isotropic diffusion (based on DarkSusy) the flux of antiprotons would be far beyond the observed flux. In this contribution it is shown that more realistic propagation models could solve this problem.

After summarizing the DMA interpretation of the excess of gamma rays, the expected antiproton flux will be discussed based on the GALPROP propagation model\textsuperscript{10} after implementing and retuning its parameters and taking into account the expected anisotropic propagation and the clumpiness of the gas distribution.

2. Gamma rays from Dark Matter Annihilation

The thermally averaged annihilation cross section for any thermal relic is known from the inverse proportionality to the relic density.\textsuperscript{2} This cross section comes out to be that of a Weakly Interacting Massive Particle (WIMP). The dark matter annihilation (DMA) is expected to yield predominantly mono-energetic quark pairs, since the kinetic energy is negligible for CDM. From the hadronization of the quarks one expects a large flux of gamma rays from the decay of the $\pi_0$ mesons, typically several tens of gamma rays per annihilation with energies of several GeV. The gamma ray spectrum from mono-energetic quarks has been studied in detail in the hadronization of quarks produced at electron-positron colliders. The DMA gamma ray spectrum is considerably harder than the background spectrum, which originates from inelastic scattering of cosmic rays (CR) on the interstellar gas. If the CR spectra are known and uniform in the Galaxy, the shape of the background gamma rays is known from accelerator experiments. The
absolute value of neither the background nor DMA is known, because of the large uncertainties in density of the interstellar medium, CR density and CDM density. Therefore the obvious way to search for DMA is to leave the absolute normalizations of the background and DMA contributions free and fit only the shapes of the background and DMA for a given sky direction.

Experimentally, the spectral shape of the diffuse Galactic gamma rays has been measured with the EGRET satellite; we use the EGRET data in the range 0.07 to 10 GeV in 8 energy bins. For the relative amount of electron- and nucleon-induced gamma rays the estimates from real data, as implemented in the publicly available “conventional” GALPROP model, can be used, so one has only one normalization constant for the background instead of separate ones for the different background components.

Comparing the background with the EGRET data shows that above 1 GeV there is a large deficit of gamma rays, which reaches more than a factor of two towards the Galactic centre. Fitting the background together with the DMA, yields a perfect fit in all sky directions for a CDM particle mass around 60 GeV. The shape fit automatically finds from the free normalizations the relative amount of background and DMA. Furthermore, the results are consistent with Supersymmetry. From the amount of excess in 180 independent sky directions one can reconstruct the CDM profile, which in turn can be used to calculate the rotation curve. The result explains the hitherto unexplained change of slope in the outer rotation curve, as shown in Fig. 1. For the halo profile one is only interested in the relative contributions in the various sky directions, so here all experimental errors.
cancel, since the EGRET satellite does not care in which direction it measures. The EGRET errors, as discussed in Ref.11 are not relevant, since we are not interested in predicting absolute gamma ray fluxes, but only fit the shapes with a free normalization. In this case only the point-to-point errors are relevant. Furthermore, since the systematic errors are dominating, every data point has approximately the same weight, so changing the total error does not change the solution for the minimum of the $\chi^2$ distribution; larger errors only decrease its value. But in the fits of around 1400 data points the $\chi^2/d.o.f$ is already well below 1 with a 7% point-to-point error, suggesting that these errors for a shape fit are already overestimated.

Uncertainties from the background, which are dominated by the solar modulation uncertainty in the primary CR spectra, are shown in Fig. 2. Note that the solar modulation depletes the CR spectrum at low energies, but fitting the shape translates this into an uncertainty mainly at high energy. This is simply because at low energy the spectrum is almost purely background, so the expectations are effectively “normalized” to this low energy data by the fit, whatever the shape of the spectrum.

Clearly the uncertainties in the background shape cannot explain the excess, if one assumes that the locally observed CR spectra are representative for the spectra outside the heliosphere after correcting for solar modulation.
For nuclei the spectra are expected to be indeed similar everywhere because the diffusion is fast compared with energy loss times. So local variations of the spectra or intensities, as proposed in Ref.\textsuperscript{12} to explain the excess, seem to us unlikely, especially since this needs in addition rather strong breaks in the CR injection spectra in order to keep the gamma rays below 1 GeV the same, but only increase the high energy gamma rays. Furthermore, these breaks are only applied to protons, not to other nuclei in order to maintain the B/C ratio. Also the “fresh” harder source component \( \propto E^{-2} \) instead of \( \propto E^{-2.7} \) is not expected to yield a significant effect, since this is only a small fraction of the total CR density. This is obvious for older Galaxies, where the amount of CR escaping to outer space (with an escape time of \( \mathcal{O}(10^7 - 10^8) \) y) should be equal to the amount of generated CR (with a source life time of \( \mathcal{O}(10^4 - 10^5) \) y), so the fresh component should be of \( \mathcal{O}(10^{-2} - 10^{-3}) \). That the shape of CR in the steady state is similar everywhere, is confirmed by a numerical solution of the diffusion equation, as used in GALPROP. For this “conventional” model of CRs having everywhere the spectrum of the locally observed one, the WIMP mass is rather well constrained (50-70 GeV), as shown on the right hand side of Fig. 2.

In summary, the gamma rays play a very special role for indirect CDM searches, since they point back to the source and are independent of propagation models. Therefore the gamma rays provide a perfect means to reconstruct the intensity (halo) profile of the CDM by observing the intensity of the gamma ray emissions in the various sky directions. This halo profile can in turn be used to check the shape of the rotation curve, thus providing a direct link between the excess of the gamma rays and the strongest evidence for CDM, the rotation curve.

3. Antiproton fluxes

Contrary to gamma rays the charged particles change their direction by the interstellar magnetic fields, energy losses and scattering. Therefore one needs a detailed propagation model to calculate the amount of particles which will arrive from the source to the detector. Charged particles usually make a random walk process by changing their direction through interaction with the galactic magnetic field, which is thought to have a larger random (turbulent) component in the interstellar space. But galactic winds may lead to a strong convective transport of these magnetic turbulences perpendicular to either side of the galactic plane, which take the charged particles with them to outer space,\textsuperscript{13} thus leading to strong anisotropic propagation. Furthermore, the transport and production of charged parti-
The antiproton fluxes and the B/C ratio from the modified GALPROP code including DMA and anisotropic propagation. Note that roughly half of the antiprotons are coming from DMA, as for the gamma rays above 1 GeV, while DMA does not contribute to the B/C ratio.

By increasing the convection perpendicular to the disk and implementing the local bubble, the local clouds and “magnetic walls” with slow diffusion in the solar neighbourhood one can change the antiproton flux by an order of magnitude, while still being consistent with the B/C ratio, as shown in Fig. 3. The DMA contribution explains the traditional EGRET “excess” of gamma rays without the need for assuming that the locally observed CR spectra are different from the CRs in the rest of the Galaxy. Here the GALPROP model was used after including DMA and retuning the diffusion and convection parameters. Traditionally these parameters have been determined by the B/C ratio and the cosmic clocks, like the $^{10}Be/^{9}Be$ ratio. The diffusion coefficient needed for the B/C ratio required a large halo with a distance of $z=4$ kpc to get a long enough trapping time for the cosmic clocks. This traps also the antiprotons from DMA, thus leading to the solution from Ref.\textsuperscript{3} using DarkSusy. This results can be reproduced with GALPROP, if the isotropic diffusion dominates. In our case the antiprotons are blown to outer space by convection, which overtake diffusion a...
few hundred parsec above the disk. In this case of large convection a one
to two orders of magnitude smaller diffusion coefficient is needed, which is
much closer to the values used in heliospheric propagation models. The
large B/C ratio is obtained by the local fluff with a size of 5 pc in the local
bubble. Note that most of the molecular gas is concentrated in large molec-
ular clouds, which occupy only a few % of the volume. These clouds act
as localized sources of all secondary particles and are particularly strong if
nearby, since the flux decreases as $1/r^2$. Naively one expects that if locally
a large amount of secondary boron nuclei are produced (by fragmentation
of CNO and heavier atoms on the gas), one expects a correspondingly large
amount of secondary antiprotons. This is not true, since the latter require
CR protons with an energy above 10 GeV (due to threshold effects), while
for rigidities of CNO nuclei below 10 GeV the fragmentation cross sections
just increase. Therefore changing the injection spectra of primary particles
below 10 GeV by 10% or changing the energy dependence of the diffusion
constants immediately changes the antiproton/B ratio for rigidities around
1 GeV by a factor of a few.

In summary, recent claims that the antiproton fluxes exclude the DMA
interpretation of the EGRET excess should be considered in the light of the
limitations of DarkSusy, which uses a simple analytical solution of the
diffusion equation with unrealistic smooth gas distributions and isotropic
diffusion coefficients. In order to allow for anisotropies in gas distributions,
convection velocities and diffusion coefficients one has to resort to numeri-
cal solutions of the diffusion equation, as implemented in GALPROP after
suitable modifications for DMA, non-equidistant grids and anisotropic dif-
fusion and convection, i.e. $D(r,z)$ and $V(r,z)$. In the latter case a consistent
flux of local CR spectra, antiproton fluxes, B/C ratio and gamma rays can
be obtained.

4. Summary and Outlook
In summary, the excess of EGRET diffuse gamma rays has all the properties
expected for DMA. Especially the excess has the shape expected for the
annihilation of 60 GeV WIMPs and the distribution of the excess over the
sky is in perfect agreement with the shape of the rotation curve of our
Galaxy, which is the hallmark of a DMA signal.

Objections against the DMA interpretation of the EGRET excess concerning a too high antiproton flux should be considered in the light of their
simple diffusion model. Our preliminary investigations show that a more
realistic propagation model can reduce the antiproton flux by more than
an order of magnitude. Therefore it is hard to use antiprotons to search for light CDM particles, which yield a soft antiproton spectrum similar to the background. However, the antiprotons are perfect to tune the many parameters in more realistic propagation models, if the CDM halo is determined from the gamma rays.

Future data on high energy gamma rays (GLAST satellite) and high energy charged particles (space experiments PAMELA and AMS) will be of great interest in order to see if this picture of DMA is confirmed, while direct DM detection experiments and the new hadron collider LHC may be able to determine independently the WIMP mass. If they all find a WIMP mass in the range suggested by the EGRET excess, this would be great.

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