Possible Indications of a Clumpy Dark Matter Halo

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We investigate if the gamma ray halo, for which recent evidence has been found in EGRET data, can be explained by neutralino annihilations in a clumpy halo. We find that the measured excess gamma ray flux can be explained through a moderate amount of clumping in the halo. Moreover, the required amount of clumping implies also a measurable excess of antiprotons at low energies, for which there is support from recent measurements by the BESS collaboration. The predicted antiproton fluxes resulting from neutralino annihilations in a clumpy halo are high enough to give an excess over cosmic-ray produced antiprotons also at moderately high energies (above a few GeV). This prediction, as well as that of one or two sharp gamma lines coming from annihilations into $\gamma\gamma$ or $Z\gamma$ can be tested in upcoming space-borne experiments like AMS and GLAST.

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Some models for structure formation in the universe predict that cold dark matter clumps may have formed at various stages of the evolution of structure. Subsequent hierarchical merging of small clumps into larger ones would eventually give rise to halos of galaxies. However, if small and dense enough, some of these dark matter clumps may have survived tidal interactions and could exist still today in the halos of galaxies including the Milky Way. A clumpy halo composed of supersymmetric dark matter particles (neutralinos) would reveal itself in conspicuous ways due to the increased annihilation rate of neutralinos into gamma rays, positrons, neutrinos and antiprotons.

Several authors have pointed out that there is a discrepancy between the measured diffuse gamma ray background in the Milky Way and the predictions of detailed emission models. A strong excess of photons with energy above 500 MeV has recently been detected towards the galactic center by the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory. Rather significant deviations from emission models in the same energy range seem to be present on a large scale as well. In a very recent analysis, Dixon et al. (hereafter Paper I) claim that in EGRET data there is a strong statistical evidence for a gamma ray halo surrounding the galaxy.

Assuming that the effect is real, some possible explanations have been addressed, such as an origin from unresolved point sources (Geminga-like pulsars are feasible candidates), an underestimate of the inverse Compton emission at high latitudes and gamma rays associated with baryonic dark matter or WIMP annihilations. We will focus on the latter and investigate the intriguing possibility that the gamma ray halo might result from pair annihilations of dark matter neutralinos, the lightest supersymmetric particle in the Minimal Supersymmetric Standard Model (MSSM) and one of the leading dark matter candidates. We will analyse the compatibility of the signal with this hypothesis and compare with the information which could be extracted from other neutralino detection methods, in particular low-energy cosmic antiprotons. Recent results from the Balloon-borne Experiment with Solenoidal Magnet Spectrometer (BESS) indeed appear to show some excess of antiprotons at low energy, a characteristic signal of neutralino annihilations.

We work in the framework of the Minimal Supersymmetric Standard Model (MSSM) as defined in Refs. More details on our notation can be found in Ref. With some simplifying assumptions we are left with 7 parameters which we allow to be varied within generous bounds. The ranges for the parameters are given in Table For each generated model, we check if it is excluded by current accelerator constraints and if it is cosmologically interesting, by which we mean models where $0.025 < \Omega h^2 < 1$, i.e. where the neutralinos can make up most of the dark matter in our galaxy without overclosing the Universe. ($\Omega$ is the energy density in units of the critical density and the present Hubble parameter is $100 h$ km $s^{-1}$ Mpc$^{-1}$.)

To get the normalization of the gamma ray flux from neutralino annihilations, we need to specify the distribution of dark matter in the galaxy. We first assume that the average dark matter density profile is spherically symmetric and can be described by

$$\rho(r) = \rho_0 \left(\frac{R_0}{r}\right)^\gamma \left[1 + \left(\frac{R_0}{a}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}$$

(1)
where $\rho_0$ is the local halo density, $R_0$ our galactocentric distance and $\alpha$ some length scale. The functional form of $\rho$ for the Milky Way cannot be fully determined from observational data \cite{10} and several choices of the parameters are acceptable. A hint on this choice may come from N-body simulations of hierarchical clustering in cold dark matter cosmologies which favour profiles that are singular towards the galactic centre. We will consider the Navarro et al. profile \cite{11} which is cuspy and has $\gamma = 1$ (it scales as $1/r^3$ at large distances) and, for comparison, the modified isothermal distribution, $(\alpha, \beta, \gamma) = (2, 2, 0)$, extensively used in dark matter detection computations. We have checked that the Kravtsov et al. profile \cite{12} which is mildly singular with $\gamma \sim 0.2$, also gives acceptable fits.

To make the analysis compatible with the existence of clumps in the halo, we consider the possibility that a fraction $f$ of the total dark matter, rather than being smoothly distributed in the halo, is concentrated in clumps. Simulations of structure formation in the early Universe do not yet have the dynamical range to give predictions for the size and density distribution of small mass clumps (we focus here on clumps of less than around $10^6$ solar masses which avoid the problem of unacceptably heating the disk \cite{13}). The formation of clumps on all scales is however a generic feature of cold dark matter models which have power on all length scales. If self-similarity is a guide, galaxy halos may form hierarchically in a similar way to that of cluster halos (see e.g. \cite{14}). The main effects of a clumpy halo can be sketched self-similarly in a similar way to that of cluster halos (see e.g. \cite{15}).

Pair annihilations of neutralinos in the dark matter halo can produce photons which are either monochromatic or with a continuum energy spectrum. The monochromatic $\gamma$s arise from the loop-induced S-wave annihilation into the $\gamma\gamma$ or $Z\gamma$ final states; the phenomenology of these processes has been studied recently in Ref. \cite{16}. The continuum contribution is on the other hand mainly obtained from pions produced in jets; these photons are expected to be much more numerous but lower in energy than the monochromatic ones \cite{10}. To model the fragmentation process and extract information on the number and energy spectrum of the photons produced we have used the Lund Monte Carlo PYTHIA 6.115 \cite{17}.

Consider a detector with an angular acceptance $\Delta \Omega$ pointing in a direction which forms an angle $\psi$ with respect to the galactic centre. The integrated $\gamma$ ray flux above an energy threshold $E_{th}$ is given by

$$\Phi_{\gamma}(E_{th}, \Delta \Omega, \psi) \simeq 1.87 \times 10^{-8} S(E_{th}) \cdot \langle J(\psi) \rangle (\Delta \Omega) \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$ (2)

In this formula we have defined a particle physics-dependent term

$$S(E_{th}) = \left( \frac{10 \text{ GeV}}{M_X} \right)^2 \int_{E_{th}}^{M_X} dE \cdot \frac{\sum_{F} \left( \frac{\varv \sigma_{F}}{10^{-26} \text{ cm}^3 \text{s}^{-1}} \right) dN_{\gamma F}}{dE},$$ (3)

where $M_X$ is the neutralino mass, $F$ are the allowed final states and for each of these $\varv \sigma_{F}$ is the annihilation rate, while $dN_{\gamma F}/dE$ is the differential distribution of produced photons. The dependence of the flux on the dark matter distribution is contained in the factor $\langle J(\psi) \rangle (\Delta \Omega)$. In a scenario with many unresolved clumps, it is possible to show that the contribution from the clumps is given by \cite{18}

$$\langle J(\psi) \rangle_{\text{cl}} (\Delta \Omega) = \frac{1}{8.5 \text{ kpc}} \frac{1}{\Delta \Omega} f \delta \int_{\Delta \Omega} d\Omega' \int_{\text{line of sight}} dl \left( \frac{\rho(l, \psi')}{0.3 \text{ GeV/cm}^3} \right),$$ (4)

in contrast to the smooth case \cite{15} where the dependence is quadratic in the density $\rho$. The relative strength of the smooth and the clumped components is determined both by the halo profile and by the parameter $f \delta$, the product of the halo fraction in clumps and their overdensity.

In Fig. 1 we show the values of $S(1 \text{ GeV})$ versus the neutralino mass for our set of supersymmetric models. Our results show a very large dispersion for the possible values of $\Sigma$, about seven orders of magnitude; the highest $S$ are for low neutralino masses, $M_X \sim 40-60 \text{ GeV}$, while for heavier neutralinos there are both the $1/M_X^2$ suppression and lower photon production rates. The highest values of the $\gamma$ ray flux are given by gaugino-like neutralinos and mixed neutralinos, whereas $S$ is generally much lower for higgsino-like neutralinos, at least in the low mass range (the opposite trend was noticed for the monochromatic photon flux, see Ref. \cite{16}). For the highest possible values of the flux $S$ scales as $1/(\Omega h^2)$ which reflects the fact that to a first approximation $\Omega h^2 \sim 1/(\varv \sigma t)$. Therefore, the maximal $S$ depends crucially on the minimal $\Omega h^2$ (which we take to be 0.025) that we judge to be cosmologically interesting. Current estimates of $\Omega$ and $h$
We focus now on the result reported in Paper I. The value of the residual flux at high latitudes shown in Fig. 3, Paper I is about $10^{-4}$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Even picking the MSSM model in our set which gives the highest $S(1\ GeV)$, it is not possible to reproduce the qualitative features in that Figure in a smooth halo scenario with any of the three halo models considered and any of the allowed values for length scale $a$ and local halo density $\rho_0$. On the other hand a many unresolved clump scenario may be compatible with the results of Paper I. We will show this through two examples.

Let us first consider an example in the low mass range, a MSSM model which has $M_\chi = 76\ GeV$, $\Omega_\chi h^2 = 0.03$, $Z_\gamma = 0.18$ and which gives $S(1\ GeV) = 1.025$. We show in Fig. 2 for this model the values of $\langle J(\psi) \rangle$ needed to fit the results in Paper I. We are considering a roughly spherical $\gamma$ ray halo and deriving the angular distribution from Fig. 3, Paper I at zero longitude. As can be seen, the present EGRET data can be quite well reproduced in our approach. Although we are not in the position of discriminating among different halo profiles, one may notice that in the case of the Navarro et al. profile, a sharp enhancement of the $\gamma$ ray flux is predicted towards the galactic centre, due to the singularity of the smooth density profile. This is a feature which may be searched for in the EGRET data (some indications of results going in that direction were given in Ref. [19]).

We find that the dark matter signal, which causes an excess of photons mainly in the energy range between a few GeV and $M_\chi$, may explain the discrepancy between the 2.75 power law fall off which is expected according to models of diffuse galactic background and the behaviour that has been mapped by EGRET up to 20 GeV. Future experiments [20,21] will be able to measure the diffuse background at much higher energies and eventually detect if there is a break in the energy spectrum at about the neutralino mass.

For the MSSM model we have chosen, the gamma lines from annihilation into $\gamma\gamma$ and $Z\gamma$ are well above the background, and their detection might be possible, especially if there is an enhancement of the dark matter density towards the galactic centre. The detection of lines, which have no plausible astrophysical background, seems to be the natural way to show conclusively whether the $\gamma$ ray halo originates from dark matter neutralino annihilations. On the other hand, the correlation between continuum and line signal strengths is very weak and the absence of the lines would by no mean imply that there cannot be a continuum signal.

Given the value of $f\delta$ needed, we have to worry about other dark matter searches and make sure that these models are not excluded already. It turns out that the signals are below present detection limits, except for the antiproton signal which we now discuss.

We have computed the antiproton signal in much the same way as the continuous gammas by using the Lund Monte Carlo PYTHIA 6.115. We have applied for the propagation the leaky box approximation with the energy dependent escape time given in Ref. [22] and used the

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**FIG. 1.** The value of $S$ versus the neutralino mass.

**FIG. 2.** The value of $\langle J(\psi) \rangle$ for a) the Navarro et al. profile and b) the isothermal sphere. The clumpyness and halo model parameters to fit the EGRET data, shown as filled circles, are given in the figure.
solar modulation model of Ref. [23].

For the example considered above the antiproton flux at 0.4 GeV in a clumpy halo with \( f \delta = 18 \) is \( \phi_\bar{p} = 1.6 \times 10^{-5} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{GeV}^{-1} \) which should be compared with the flux measured by BESS \( \phi_\bar{p} = 1.4_{-0.9}^{+2.9} \times 10^{-6} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{GeV}^{-1} \) at the same energy. It may be tempting to conclude that this model is already excluded since it gives a too high antiproton flux, but one has to keep in mind the big uncertainties involved, mainly in the antiproton propagation. In particular, it is not clear how large a fraction of antiprotons generated in the halo (i.e. outside the galactic disk) can penetrate the wind of cosmic rays leaving the disk [24]. It is interesting that the antiproton flux is within an order of magnitude of the reported BESS flux, which shows some of the characteristics (pile-up at low energy) expected for neutralino-induced antiprotons [3].

Since we have found in our calculations that the antiproton flux strongly correlates with the continuous gamma flux for a given supersymmetric model, it seems impossible to reduce the antiproton flux maintaining high continuous gamma flux at sub-100 GeV neutralino mass. If the overproduction of antiprotons seems uncomfortably high, it is however possible to resolve this by going to higher neutralino masses.

We thus choose as our second example an MSSM model which has a large mass, \( M_\chi = 503 \, \text{GeV} \), \( \Omega h^2 = 0.03 \), \( Z_g = 0.04 \) and which gives \( S(1 \, \text{GeV}) = 0.05 \, \text{ph} \). The necessary rescaling for this model is \( f \delta = 427 \) for which the antiproton flux at 0.4 GeV is \( \phi_\bar{p} = 1.7 \times 10^{-6} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{GeV}^{-1} \), i.e. within the 1σ error bars of the BESS measurement. For these higher mass models, there may be a problem in explaining a high gamma ray flux in the lower energy interval 0.3–1.0 GeV (this interval is however subject to larger uncertainties). An intermediate mass model in which the antiproton flux limit by BESS is mildly violated might of course be considered. More data is obviously needed to make firmer statements.

We remark that for this particular model, the spin-independent cross section on nucleons is \( 0.15 \times 10^{-4} \, \text{pb} \), very close to the limit given by the most sensitive NaI experiment [28]. For other models giving similar gamma and antiproton rates, however, the direct detection rates are much lower.

It is interesting to note that for the high-mass neutralino, also a high-energy excess of antiprotons is potentially measurable. This is illustrated in Fig. 3, where a compilation of present data (3 and references therein) is shown together with the predictions of cosmic-ray induced background (the mid-range of the predictions of [24]), and the flux in our second example. As can be seen, present data are not yet conclusive. However, an interesting feature of the high-mass neutralino result is that the maximum of the antiproton flux is shifted towards higher energies by 1–2 GeV compared with the low mass case. Also, the fall-off with energy above the peak is considerably slower than for the background. Indeed, our second model fits quite nicely this higher-energy part of the present data. It should be noted that at these energies, the effects of galactic and solar wind modulation is less severe than at sub-GeV energies, making the predictions more trustworthy. These features should definitely be investigated in the upcoming antiproton measurements [27,20].

Although the interpretation of the measured excess in cosmic gamma rays and antiprotons in terms of neutralino annihilation contains elements of speculation at the present time, it is reassuring that upcoming experiments will be in a position to more firmly confirm or rule out this hypothesis. For instance, the proposed Gamma-ray Large Area Space Telescope (GLAST) [21] will have spectral and angular resolution enough to search for gamma ray lines in the direction of the center of the galaxy. Also, if the explanation lies in a clumpy halo, a large-exposure experiment like GLAST eventually may resolve individual large clumps as bright gamma-ray spots on the sky. The antiproton spectrum will soon be measured with higher accuracy as well in the Alpha Magnetic Spectrometer (AMS) [23] and PAMELA [27] experiments. Also, upcoming direct detection experiments may in favourable cases be sensitive to these dark matter candidates. Finally, improved N-body simulations of structure formation in cold dark matter models may give a better assessment of the credibility of clumpy halo models.

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[1] D.D. Dixon et al., astro-ph/9803237, Paper I.
[2] S.D. Hunter et al., ApJ 481 (1997) 205.
[3] D.L. Bertsch et al., ApJ 416 (1993) 587.
[4] P. Sreekumar et al., ApJ 494 (1998) 523.
[5] H. Mayer-Hasselwander, talk at “Matter, anti-matter and dark matter” workshop, Trento, 1998.
[6] H. Matsunaga et al., Proc. 25th International Cosmic Ray Conference (1997) 4, 225.
[7] H.E. Haber and G.L. Kane, Phys. Rep. 117 (1995) 75.
[8] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267 (1996) 195.
[9] J. Edsjö and P. Gondolo, Phys. Rev. D56 (1997) 1879.
[10] W. Dehnen and J. Binney, MNRAS 294 (1998) 429.
[11] J.F. Navarro et al., ApJ 462 (1996) 563.
[12] A.V. Kravtsov et al., astro-ph/9708176.
[13] J. Silk and A. Stebbins, ApJ 411 (1993) 439.
[14] G. Tormen et al., astro-ph/9712222.
[15] L. Bergström, P. Ullio and J. Buckley, Astroparticle Phys. in press, astro-ph/9712318.
[16] H.-U. Bengtsson et al., Nucl. Phys. B346 (1990) 129; V. Berezinsky et al., Phys. Lett. B325 (1994) 136; P. Chardonnet et al., ApJ 454 (1995) 774.
[17] T. Sjöstrand, Comp. Phys. Comm. 82 (1994) 74;
[18] L. Bergström, J. Edsjö, P. Gondolo and P. Ullio, in preparation.
[19] D.N. Schramm and M.S. Turner, Rev. Mod. Phys. 70 (1998) 303.
[20] R. Battiston, N.I.M. in press, hep-ex/9708039.
[21] http://www-glast.stanford.edu.
[22] P. Chardonnet et al., Phys. Lett. B384 (1996) 161.
[23] J.S. Perko, A&A 184 (1987) 119.
[24] V.S. Ptuskin et al., Astron. Astrophys. 321 (1997) 434.
[25] R. Bernabei et al., Phys. Lett. B389 (1996) 757.
[26] T.K. Gaisser and R.K. Schaefer, ApJ 394 (1992) 174.
[27] O. Adriani et al., Proc. 25th International Cosmic Ray Conference (1997) 5, 49.