Galactic propagation of positrons from particle dark-matter annihilation

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Abstract

We have made a calculation of the propagation of positrons from dark-matter particle annihilation in the Galactic halo for different models of the dark matter halo distribution using our 3D code. We show that the Green's functions are not very sensitive to the dark matter distribution for the same local dark matter energy density. We compare our predictions with computed cosmic ray positron spectra ("background") for the "conventional" cosmic-ray (CR) nucleon spectrum which matches the local measurements, and a modified spectrum which respects the limits imposed by measurements of diffuse Galactic γ-rays, antiprotons, and positrons. We conclude that significant detection of a dark matter signal requires favourable conditions and precise measurements unless the dark matter is clumpy which would produce a stronger signal. Although our conclusion qualitatively agrees with that of previous authors, it is based on a more realistic model of particle propagation and thus reduces the scope for future speculations. Reliable background evaluation requires new accurate positron measurements and further developments in modelling production and propagation of cosmic ray species in the Galaxy.

1   Introduction:

Investigations of galaxy rotation, big-bang nucleosynthesis, and large-scale structure formation imply that a significant amount of the mass of the universe consists of non-luminous dark matter (Trimble 1989). Among the favored particle dark matter candidates are so-called weakly interacting massive particles (WIMPs), whose existence follows from supersymmetric models (see Jungman, Kamionkowski, & Griest 1996 for a review). A pair of stable WIMPs can annihilate into known particles and antiparticles and it may be possible to detect WIMPs in the Galactic halo by the products of their annihilations. Though the microphysics is quite well understood and many groups make sophisticated calculations of the spectra of annihilation products for numerous WIMP candidates which include many decay chains (e.g., Baltz & Edsjö 1998), there are still uncertainties in the macrophysics which could change the estimated fluxes of WIMP annihilation products by 1–2 orders of magnitude, making predictions for their detection difficult. The most promising is perhaps the positron signal since it can appear at high energies where the solar modulation is negligible, but its strength depends on many details of propagation in the Galaxy. The "leaky box" model is often used (e.g., Kamionkowski & Turner 1991), a simplified approach which may not be applicable in the case of positrons. On the other hand, progress in CR positron measurements is anticipated since several missions operating or under construction are capable of measuring positron fluxes up to 100 GeV (e.g. experiments gas-RICH/CAPRICE: Barbiellini et al. 1997, and PAMELA: Adriani et al. 1997). Therefore, more accurate calculation of the positron propagation is desirable.

We have developed a numerical method and corresponding computer code (GALPROP) for the calculation of Galactic CR propagation in 3D (for an overview of our approach and results see Strong & Moskalenko 1999, and also papers OG 2.4.03, OG 3.2.18 in proceedings of this conference). Briefly, the idea is to develop a model which simultaneously reproduces observational data of many kinds related to cosmic-ray origin and propagation: directly via measurements of nuclei, antiprotons, electrons, and positrons, indirectly via γ-rays and synchrotron radiation. Here we use our model for calculation of positron propagation in different models of the dark matter halo distribution (Moskalenko & Strong 1999). To be specific we will discuss neutralino dark matter, although our results can be easily adopted for any other particle dark matter candidate.

2 Green's functions:

The positron flux at the solar position is given by

$$\frac{dF}{dE} = \int d\epsilon\, G(E,\epsilon) \sum_i B_i f_i(\epsilon) \quad [\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}], \tag{1}$$

where $f(\epsilon)$ is the source function which describes the spectrum of positrons from neutralino annihilation, $G(E,\epsilon)$ is the Green's function for positron propagation in the Galaxy, and B_i is the branching ratio into a given final state i. The Green's function thus includes all details of the dark matter mass distribution, neutralino annihilation cross section, and Galactic structure (diffusion coefficient, spatially and energy dependent energy losses etc.). We can write it in the form:

$$G(E,\epsilon) = \langle \sigma v \rangle \frac{\rho_0^2}{m_\chi^2} g(E,\epsilon) \quad [\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}], \tag{2}$$

where $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section, ρ_0 is the local dark matter mass density, m_χ is the neutralino mass, and we have introduced a function $g(E,\epsilon)$ which describes the positron propagation for a given dark matter mass density distribution in the halo.

Following Kamionkowski and Kinkhabwala (1998) we consider three different dark matter mass density profiles which match the Galactic rotation curve. The canonical "isothermal" sphere profile, the spherical Evans model, and an alternative model. For each given model we calculate the function $g(E,\epsilon)$ defined in Eq. (2), which gives the positron flux at the solar position corresponding to the positron source function in the form of a Dirac δ-function in energy. The positron propagation is calculated in a model which was tuned to match many available astrophysical data (Strong & Moskalenko 1998, Strong, Moskalenko, & Reimer 1999). Since the halo size in the range $z_h = 4 - 10$ kpc is favored by our analyses of B/C and ^{10}Be/^{9}Be ratios and diffuse Galactic γ-ray emission, we consider two cases $z_h = 4$ and 10 kpc which provide us with an idea of the possible limits. The preferred neutralino mass range following from accelerator and astrophysical constraints is $50\,\mathrm{GeV} < m_\chi < 600\,\mathrm{GeV}$ (Ellis 1998), and we consider positron energies $\epsilon \le 824$ GeV which cover this range.

Fig. 1 shows our calculated g-functions for different models of the dark matter distribution: "isothermal", Evans, and alternative. The curves are shown for two halo sizes $z_h = 4$ and 10 kpc and several energies $\epsilon = 1.03$,
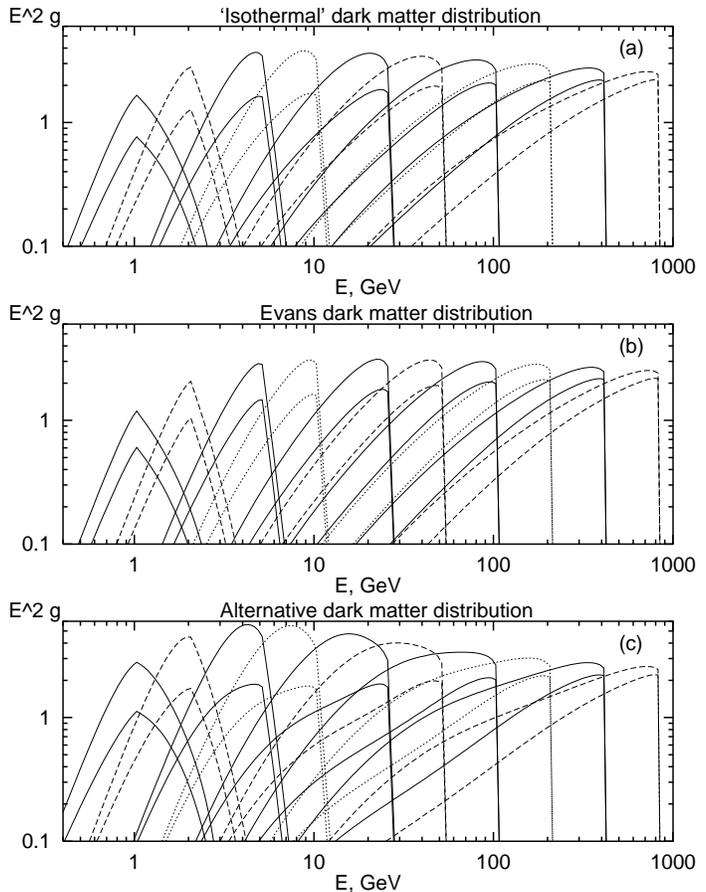

Figure 1: Calculated g-functions for different models of the dark matter distribution: (a) "isothermal", (b) Evans, (c) alternative. Upper curves $z_h = 10$ kpc, lower curves $z_h = 4$ kpc, $\epsilon = 1.03, 2.06, 5.15, 10.3, 25.8, 51.5, 103.0, 206.1, 412.1, 824.3$ GeV. The units of the abscissa are 10^{25} GeV cm sr^{-1}.

$2.06, 5.15, 10.3, 25.8, 51.5, 103.0, 206.1, 412.1, 824.3$ GeV. At high energies, increasing positron energy losses due to the inverse Compton scattering compete with the increasing diffusion coefficient, while at low energies increasing energy losses due to the Coulomb scattering and ionization (Strong & Moskalenko 1998) compete with energy gain due to reacceleration. The first effect leads to a smaller sensivity to the halo size at high energies. The second one becomes visible below ~ 5 GeV and is responsible for the appearance of accelerated particles with $E > \epsilon$.
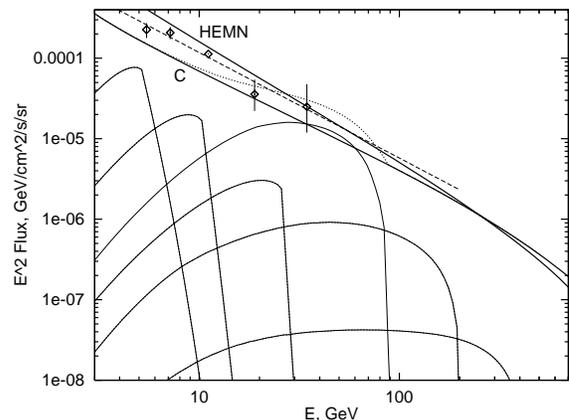
It is interesting to note that for a given initial positron energy all three dark matter distributions provide very similar values for the maximum of the g-function (on the $E^2 g(E, \epsilon)$ scale), while their low-energy tails are different. This is a natural consequence of the large positron energy losses. Positrons contributing to the maximum of the g-function originate in the solar neighbourhood, where all models give the same dark matter mass density. The central mass density in these models is very different, and therefore the shape of the tail is also different since it is produced by positrons originating in distant regions. As compared to the isothermal model, the Evans model produces sharper tails, while the alternative model gives more positrons in the low-energy tail. At intermediate energies (~ 10 GeV) where the energy losses are minimal, the difference between $z_h = 4$ and 10 kpc is maximal. Also at these energies positrons from dark matter particle annihilations in the Galactic center can contribute to the predicted flux. This is clearly seen in the case of the alternative model with its very large central mass density (Fig. 1c, $z_h = 10$ kpc).

3 Positron fluxes:

An important issue in the interpretation of the positron measurements is the evaluation of the "background", positrons arising from CR particle interactions with interstellar matter. Though the parameters of the propagation and the Galactic halo size can be fixed in a self-consistent way using CR isotope ratios, the ambient CR proton spectrum on the Galactic scale remains quite uncertain. The only possibility to trace the spectrum of nucleons on a large scale is to observe secondary products such as diffuse γ-rays, positrons, and antiprotons.

In order to show the effect of varying of the ambient proton spectrum, we compare our results with two models for the CR positron "background". These are a "conventional" model (model C) which reproduces the local directly measured proton and Helium spectra above 10 GeV (where solar modulation is small), and a model with modified nucleon spectrum (model HEMN), which is flatter below 20 GeV and steeper above, and results from our analysis of Galactic diffuse γ-ray emission. The "background" spectra are slightly dependent on the halo size. Since all secondary particles are produced in the Galactic plane, increasing the halo size results only in a small decrease of the flux at high energies due to larger energy losses. The propagation parameters for these models are given in Strong & Moskalenko (1998) and Strong, Moskalenko, & Reimer (1999), and the formalism for calculation of secondary positrons is described in Moskalenko & Strong (1998).

Figure 2: Our predictions for two CR positron "background" models (C and HEMN: heavy solid lines), and positron signals from neutralino annihilation for $m_\chi = 5.15, 10.3, 25.8, 103.0, 206.1, 412.1$ (thin solid lines): (a) $z_h = 4$ kpc, (b) $z_h = 10$ kpc. In the case of $m_\chi = 103.0$ GeV, the signal plus background (model C) is shown by the dotted line. Data and the best fit to the data (dashes) are from Barwick et al. (1998, HEAT collaboration).

We do not intend to make sophisticated calculations of positron spectra resulting from numerous decay chains such as best done by, e.g., Baltz & Edsjö (1998) for many WIMP candidates. Instead, for illustration purposes, we simplify our analysis by treating the annihilation to $W^\pm$ and Z^0-pairs. For $m_\chi < m_W$ we consider only the direct annihilation to $e^+ e^-$ pairs. In the first case we use the cross sections for a pure Higgsino (Kamionkowski & Turner 1991), in the latter case we take $B \cdot \langle \sigma v \rangle =$

3×10^{-28} cm^3 s^{-1} and monoenergetic positrons. These parameters can be considered as optimistic, but possible. To maximize the signal we further choose the Galactic halo size as 10 kpc.

Fig. 2 shows our predictions for the two CR positron "background" models together with HEAT data (Barwick et al. 1998) and positrons from neutralino annihilation. It is seen that the predicted signal/background ratio has a maximum near $m_\chi \sim m_W$, while even in the "conventional" model the background is nearly equal to the signal at its maximum. It is however interesting to note that our calculations in this model show some excess in low energy (≤ 10 GeV) positrons where the measurements are rather precise but the solar modulation is also essential. If this excess testifies to a corresponding excess in interstellar space and if the positron background correspond to our "conventional" calculations, it could be a hint for the presence of the dark matter (Baltz & Edsjö 1998, Coutu et al. 1999). Our HEMN model fits the HEAT data better (no excess) and thus provides more background positrons. (This shows that in principle a good fit to positron data, which is consistent also with other measurements such as γ-rays and antiprotons is possible without any additional positron source.) Under such circumstances a significant detection of a weak signal would require favourable conditions and precise measurements. Though this conclusion qualitatively agrees with that of Baltz and Edsjö (1998) and several earlier papers, it is based on a more realistic model of particle propagation and thus reduces the scope for future speculations.

4   Conclusions:

Our propagation model has been used to study several areas of high energy astrophysics. We use this model for the calculation of positron propagation in different models of the dark matter halo distribution. We have shown that the Green's functions are not very sensitive to the dark matter distribution for the same local dark matter energy density. This is a natural consequence of the large positron energy losses. We compare our predictions with the computed CR positron "background" for two models of the CR nucleon spectrum. A correct interpretation of positron measurements requires reliable background calculations and thus emphasizes the necessity for further developments in modelling production and propagation of CR species in the Galaxy.

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