Cosmic-Ray Positrons from Annihilation of Weakly Interacting Massive Particles in the Galaxy

Allan J. Tylka[(a)]
Universities Space Research Association, Columbia, Maryland 21044
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The production of cosmic-ray positrons from the annihilation of weakly interacting massive particles (WIMP's) is considered. Conventional supersymmetric-neutralino annihilation generally yields an unobservably small e^+ flux. However, a massive WIMP ($\gtrsim 20$ GeV) with a large annihilation cross section into a single e^+e^- pair produces a distinctive and observable shelf in the cosmic-ray e^+ spectrum. Only Dirac neutrinos obviously generate such a feature, but it may also appear in more elaborate neutralino models. Such models are constrained by upper limits on the low-energy antiproton flux.

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One of the most important questions in astrophysics is the nature of the dark matter which apparently comprises galactic halos and may account for more than 90% of the mass of the Universe.[1] Several lines of argument[2] suggest that this dark matter is not baryonic and may therefore be in the form of exotic particle species surviving from the early Universe. Particle theory has provided many dark-matter candidates, among which are weakly interacting massive particles (WIMP's, hereafter referred to as χ particles). A particularly interesting class of WIMP's consists of the supersymmetric neutralinos,[3] which may be photinos ($\tilde{\gamma}$), Higgsinos ($\tilde{h}$), or mixed states containing these. For a broad range of supersymmetry parameters, a cosmologically significant number of χ particles should exist today.[4] These χ particles would have been incorporated into galactic halos, where they occasionally annihilate. The final states thus produced are quark-antiquark pairs, which then fragment into jets of hadrons, and lepton-antilepton pairs. Protons and antiprotons, γ rays, electrons and positrons, and various neutrinos and antineutrinos remain after the decay of unstable particles. The cosmic $\bar{p}$, γ, e^+, and ν spectra may thus contain signatures of $\chi\chi$ annihilation.[5]

Silk and Srednicki[6] first suggested that photino annihilation could roughly account for the reported cosmic-ray positron excess below 1 GeV, but the annihilation rate they used has been ruled out by accelerator limits[7] on the squark mass. A more thorough study of e^+ production, including analytic estimates of the e^+ spectrum, was made by Rudaz and Stecker.[8] By taking a $\chi\chi$ annihilation rate large enough to account for a reported excess[9] of low-energy antiprotons, they found that 15-GeV Higgsinos might give an e^+ flux comparable to that produced by cosmic-ray interactions in the interstellar medium. More recent measurements[10,11] have observed no antiproton excess, and a new analysis[12] of $\bar{p}$ production in $\chi\chi$ annihilation implies a virtually undetectable e^+ flux from neutralino annihilation.

We present here a study of cosmic-ray e^+ production from $\chi\chi$ annihilation in the galaxy. We show that neutralino annihilation generally yields no more than a few percent of e^+ flux from cosmic-ray (CR) interactions. The one exception to this general conclusion comes from a massive WIMP ($M_\chi \gtrsim 20$ GeV) with a large cross section for producing a single e^+e^- pair. These annihilations would yield a sharp break[13] in the CR e^+ spectrum at energy equal to M_χ. Only massive Dirac neutrinos (ν_D) obviously generate such a feature. Unlike neutralinos, there is no strong theoretical motivation for such particles. In fact, there is significant experimental evidence against them as a major component of the galactic dark matter.[14-16] Nevertheless, this feature is worth noting because (1) it may appear in more elaborate neutralino models and thus provide a distinctive signature of $\chi\chi$ annihilation and, (2) it offers a possible explanation for the reported rise[17-19] in the e^+ fraction above 10 GeV.

In the so-called "leaky-box" approximation, the propagation of CR positrons is described by the equation[20]

$$\frac{n(E)}{\tau(E)} - \frac{d}{dE}[n(E)b(E)] = q(E)\,, \tag{1}$$

where $n(E)$ is the differential positron density, $\tau(E)$ is the energy-dependent containment time in the propagation volume, $b(E) = -dE/dt > 0$ is the energy-dependent rate of energy loss, and $q(E)$ is the e^+ source function. This homogeneous approximation neglects position dependence and thus requires values averaged over the propagation volume.

The solution of Eq. (1) is given by

$$n(E) = \int_E^\infty \frac{q(E')}{b(E)} \exp\left(-\int_E^{E'} \frac{dx}{\tau(x)b(x)}\right) dE'\,. \tag{2}$$

The e^+ flux is $j(E) = cn(E)/4\pi$. We now discuss estimates for $\tau(E)$ and $b(E)$.

Propagation studies of CR nuclei indicate an energy-dependent containment time,[21] while studies of high-energy electrons[22] favor no energy dependence. For simplicity, we adopt $\tau(E) = \tau_0$, a constant. Our conclusions are not sensitive to this assumption. The value of $\tau_0 = \tau_8 \times 10^8$ yr may be estimated from studies of CR nuclei, in particular the abundance[23] of the radioactive nuclide ^{10}Be. If cosmic rays are effectively confined to the galactic disk, these results imply $\tau_8 \sim 0.1$. On the other hand, if cosmic rays diffuse through a halo[24] of radius ~ 10 kpc, $\tau_8 \sim 1$. Studies of cosmic-ray electrons and stable secondary nuclei[25] also suggest $0.1 < \tau_8 < 1$.

The energy loss of relativistic electrons may be written[20]

$$b(E) = [2.7n_{\rm H} + 7.3n_{\rm H}E + (U_{\rm rad} + U_{\rm mag})E^2] \times 10^{-16}\,\text{GeV/s}, \quad (3)$$

where $n_{\rm H}$ is the hydrogen density in atoms/cm^3, E is the electron energy in GeV, $U_{\rm rad}$ is the ambient photon energy density, and $U_{\rm mag}$ is the magnetic field energy density, both in eV/cm^3. In this equation, the four terms represent, respectively, ionization, bremsstrahlung, inverse Compton scattering, and synchrotron radiation. Ionization is the dominant mechanism only at $E < 0.1$ GeV, so we ignore its logarithmic energy dependence and take its value at $E = 0.05$ GeV.

For propagation essentially confined to the galactic disk, typical values[22,26] in Eq. (3) are $n_{\rm H} = 0.3$ atoms/cm^3, $U_{\rm mag} = 0.2$–0.9 eV/cm^3, and $U_{\rm rad} = 0.8$–1.3 eV/cm^3. For propagation in the galactic halo, much smaller values,[24] such as $n_{\rm H} = 0.01$ atoms/cm^3, $U_{\rm mag} = 0.05$ eV/cm^3, and $U_{\rm rad} = 0.25$ eV/cm^3 (from the 2.7-K microwave background) are appropriate. In this calculation, we are dealing with positrons which are born in the halo and presumably spend a significant amount of time there before reaching us here in the disk. We therefore adopt intermediate values, namely $n_{\rm H} = 0.1$ atoms/cm^3, $U_{\rm mag} = 0.2$ eV/cm^3 (corresponding to a mean perpendicular magnetic field strength of about 3 μG), and $U_{\rm rad} = 0.4$ eV/cm^3 (allowing for some visible and infrared radiation as well as the microwave background).

The positron source function due to $\chi\chi$ annihilation at $\mathbf{r}$ may be written

$$q_e(E,\mathbf{r}) = [\rho_\chi(\mathbf{r})/M_\chi]^2 \langle \sigma v_{\rm rel}\rangle S_e(E), \quad (4)$$

where $\rho_\chi(\mathbf{r})$ is the mass density of χ particles at $\mathbf{r}$, $\langle \sigma v_{\rm rel}\rangle$ is the present-day thermally averaged $\chi\chi$ annihilation cross section, and $S_e(E)$ is the differential positron spectrum per annihilation. For Dirac neutrinos, $q_e(E,\mathbf{r})$ is reduced by an additional factor of 4, since particles and antiparticles are distinct. The leaky-box model requires that $q_e(E,\mathbf{r})$ be averaged over the propagation volume, which we take to be a sphere of 10-kpc radius. We use[27] $\rho_{\rm dark}(r) = \rho_0[1 + (r/a)^2]^{-1}$ with $a = 8$ kpc and $\rho_0 = 0.5$ GeV/cm^3 (with an uncertainty in ρ_0 of about a factor of 2). This gives a root-mean-square value $\langle \rho_{\rm dark}\rangle = 0.56\rho_0 \sim 0.3$ GeV/cm^3, which we put in place of $\rho_\chi(\mathbf{r})$ in Eq. (4).

We adopt standard estimates for the annihilation cross section $\langle \sigma v_{\rm rel}\rangle = \langle \sigma v\rangle_{26} \times 10^{-26}$ cm^3/s. In particular, in the simplest models[3,6] in which all scalar partners have a common mass $M_{\rm SP}$, $\langle \sigma v\rangle_{26} = 0.2[M_{\rm SP}/(80\text{ GeV})]^{-4}$ for photinos with mass between that of the bottom and top quarks. Similarly, for Higgsinos,[3,8] $\langle \sigma v\rangle_{26} = \xi^2 Z(M_h)$, where $\xi^2 \le 1$ is an unknown Higgs symmetry-breaking factor, M_h is the Higgsino mass, and $Z(M_h)$ is the familiar Z_0 propagator enhancement. For massive Dirac neutrinos,[28] $\langle \sigma v\rangle_{26} = 0.19(M_\nu/1\text{ GeV})^2 Z(M_\nu)$, where M_ν is the neutrino mass.

To calculate $S_e(E)$, we have used the Lund Monte Carlo program,[29] which has been employed in other recent studies[12,30] of $\chi\chi$ annihilation. For $q\bar{q}$ final states, the Lund program uses a QCD-based color string model to produce hadrons. Unstable particles decay according to known branching ratios. We have run the Lund program for $\chi = \tilde{\gamma}, \tilde{h}, \nu_D$ over a range of masses and fitted high-statistics e^+ spectra by simple functional forms.[12] The e^+ source functions for the annihilation of 10-GeV $\tilde{\gamma}$'s, 20-GeV $\tilde{h}$'s, and 30-GeV ν_D's (with $\langle \sigma v\rangle_{26}$ as discussed below) are shown in Fig. 1.

The Lund program gives the e^+ continuum from the decay of heavier particles. In general, $\chi\chi$ can also directly annihilate into a single e^+e^- pair, which would appear in the e^+ source spectrum as a δ function at $E = M_\chi$. After propagation, this produces a rising shelf with a sharp break at M_χ in the CR e^+ spectrum. For neutralinos, the branching ratio B for $\chi\chi \to e^+e^-$ is generally[4] about 10^{-5}, and this shelf is unobservable. For Dirac neutrinos $B(\nu_D\bar{\nu}_D \to e^+e^-) = 3\%$, and this shelf becomes a striking feature of the e^+ spectrum.

We also show in Fig. 1 the interstellar e^+ fluxes after

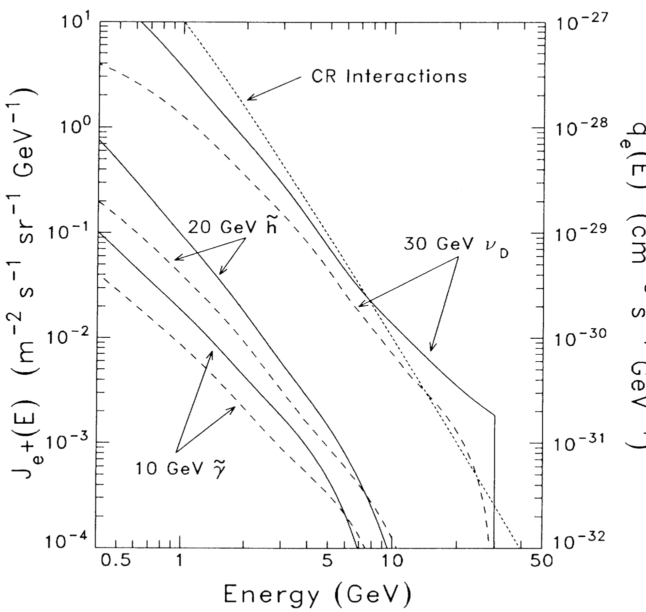

FIG. 1. The e^+ continuum source function from $\chi\chi$ annihilation before propagation (dashed curves and right-hand scale) and the interstellar e^+ flux after propagation (solid curves and left-hand scale), calculated with $\tau_8 = 0.3$ and other parameters as given in the text. The e^+ flux from CR interactions (Ref. 26) in the interstellar medium is also shown.

propagation and the calculated e^+ flux from CR interactions.[26] (The observed e^+ flux is somewhat higher.) For $\tilde{\gamma}\tilde{\gamma}$ annihilation, we used $\langle\sigma v\rangle_{26}=0.2$, consistent with recent experimental limits[7] on $M_{\rm SP}$. For $\tilde{h}\tilde{h}$ annihilation, we used the "generic" cross section,[8] with $\xi^2=1$ and $\langle\sigma v\rangle_{26}=1.6$. Since a larger annihilation rate in the early Universe leaves a smaller remnant cosmological density, generally $\Omega_\chi h^2 \sim \langle\sigma v\rangle^{-1}$. These $\langle\sigma v\rangle_{26}$ values correspond to present-day cosmological densities[31] $\Omega_\chi h_{50}^2=1$ and 0.2 for the $\tilde{\gamma}$ and $\tilde{h}$, respectively. The $\tilde{\gamma}$ and $\tilde{h}$ curves in Fig. 1 are thus close to upper limits on the e^+ flux from neutralino annihilation if the χ particles make a significant contribution to the cosmological dark matter. Since these fluxes are $\sim 1\%$ or less of the e^+ flux from CR interactions, we see that $\chi\chi$ annihilation will generally yield an unobservable e^+ flux for $\Omega_\chi h_{50}^2$ greater than a few percent. Conversely, the $\nu_D\bar{\nu}_D$ annihilation yields a substantial e^+ flux because $\langle\sigma v\rangle_{26}=500$ at $M_\nu=30$ GeV, corresponding[28] to $\Omega_\nu h_{50}^2 \sim 0.1$.

To compare directly to data, we convert our e^+ spectra to an energy-dependent positron fraction, $e^+/(e^- + e^+)$, as observed at Earth. For the denominator, we use the observed interstellar[26] $e^- + e^+$ spectrum. We add together the e^+ fractions from $\chi\chi$ annihilation and CR interactions, and we account for solar modulation with the force field approximation.[32]

Figure 2 shows our results for 30-GeV Dirac neutrinos with three different values of τ_8, along with the available data at $E > 0.4$ GeV. (At lower energies the calculations are sensitive to the details of the propagation and solar modulation.) The positron shelf from $\nu_D\bar{\nu}_D \to e^+e^-$ is clearly evident in the calculations. The height of this feature at $E=M_\nu$ varies inversely with $b(M_\nu)$ but is independent of τ_8. Reasonable values of τ_8 can describe the rising e^+ fraction above 5 GeV, which is indicated by some experiments[17-19] and unaccounted for by standard models of e^+ production by CR interactions.[26]

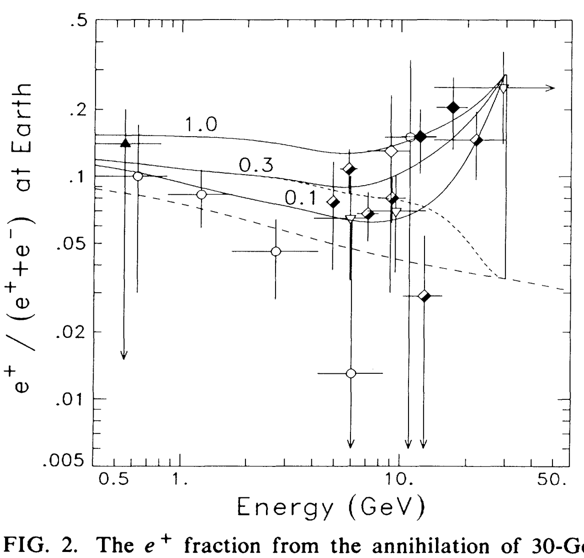

FIG. 2. The e^+ fraction from the annihilation of 30-GeV Dirac neutrinos for three values of τ_8 (solid curves). The short-dashed line shows the $\tau_8=0.3$ curve *without* the e^+ δ-function contribution. The long-dashed line shows the contribution from e^+ production in CR interactions (Ref. 26). The data points are from the following: Ref. 17 (open diamond); Ref. 18 (open triangles); Ref. 19 (solid diamonds); Ref. 33 (solid triangle); Ref. 34 (open circles); Ref. 35 (half-filled diamonds).

Although this e^+ signature of $\chi\chi$ annihilation is certainly intriguing, several comments are in order. First, the currently available data have large error bars, and better measurements, such as those proposed[36] for the Space Station's Astromag[37] facility, are needed. Second, there are less exotic explanations of the rising e^+ fraction. Mueller and Tang[19] have noted that the e^+ fraction begins to rise at the same energy where the overall $e^- + e^+$ spectrum starts to steepen relative to CR protons. They suggest that the CR e^- spectrum is actually steepening (perhaps due to synchrotron losses in the strong magnetic fields at the acceleration sites) while the e^+ spectrum continues to follow the same slope as the protons whose interactions produce them. Thus, the rising e^+ fraction may reflect a deficit of electrons, not an excess of positrons. In this scenario, the e^+ fraction should rise to a plateau value of 0.5, independent of energy. The Astromag experiments will measure the CR e^+ spectrum up to 500 GeV and thus distinguish between this explanation and the $\chi\chi$ annihilation scenario.

Of the χ candidates considered here, only massive Dirac neutrinos have a sufficiently large cross section for $\chi\chi \to e^+e^-$ ($\sim 10^{-25}$ cm^3/s) to give the high-energy e^+ feature. Several experiments[14-16] suggest that massive Dirac neutrinos cannot be a major component of the local dark matter. The most stringent limits[14] indicate that a 30-GeV Dirac neutrino cannot contribute more than $\sim 10\%$ of the local value of $\rho_{\rm dark}$. Thus, it seems highly unlikely that Dirac neutrinos *per se* can be used to generate a large high-energy e^+ flux. Neutralinos have too small a branching ratio into $\chi\chi \to e^+e^-$, at least in the simplest supersymmetric models considered here. However, it may be possible to enhance $B(\chi\chi \to e^+e^-)$ in more complicated models with carefully chosen parameters.[38]

Any scenario for enhancing $B(\chi\chi \to e^+e^-)$ faces other difficulties. Since $B(\chi\chi \to e^+e^-)$ larger than about 10% seems highly contrived, the *total* annihilation cross section in such models must be on the order of 10^{-24} cm^3/s. Such a large annihilation cross section means that the present-day cosmological density of these particles must be less than $\sim 1\%$ of the critical density. Such particles may exist; but since the dark matter in galactic halos and groups of galaxies[5] yields $\Omega \approx 0.02$–0.2, they do not solve the dark-matter problem.

Finally, there is an observational constraint on such models. In general, such a large partial cross section into e^+e^- pairs implies a comparable cross section for

$q\bar{q}$ pairs (unless the model is very carefully engineered). These quarks will produce cosmic-ray antiprotons. Without details of such a model (viz., the branching ratios into various final states) one cannot calculate a precise $\bar{p}$ spectrum. However, one can guess that it might not be too different from that for Dirac neutrinos. Following the methods of Ref. 12, we have calculated the $\bar{p}$ spectrum for 30-GeV Dirac neutrinos. Taking a $\bar{p}$ containment time of only 10^7 yr and using the $\chi\chi$ annihilation rate suggested by the rising e^+ fraction, we estimate that the observed $\bar{p}/p$ ratio at a few hundred MeV would be about 5×10^{-5}. This exceeds the current experimental upper limit[10] of 3.5×10^{-5}.

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[(a)]Mailing address: Code 4154, Gamma and Cosmic Ray Astrophysics Branch, Naval Research Laboratory, Washington, DC 20375-5000.

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