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Electrons and γ rays from near-solar supersymmetric dark matter annihilations

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The electron and γ-ray energy spectrum created from the annihilation of supersymmetric dark matter near the Sun is computed. Their predicted fluxes and the potential modification of the electron spectrum by solar magnetic fields are compared with previous astrophysical measurements and with future measurements by the Milagro and GLAST experiments. [S0556-2821(99)03112-4]

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I. INTRODUCTION

A candidate for dark matter is the lightest supersymmetric particle [1], possibly the neutralino $\tilde{\chi}^0$. The absence of supersymmetry at electron positron colliders sets lower limits on the supersymmetric mass of 80 GeV [2], the convergence of coupling constants sets an upper limit of 10 TeV [3], and the presence of supersymmetric matter in the early universe sets an upper limit of about 7 TeV [4]. Two neutralinos can annihilate into various particles. Previous studies have explored possible neutralino signals such as increased ratio of positrons versus electrons from galactic annihilations [5,6], neutrinos from inner-solar annihilations [7], γ rays from highly galactic centered annihilations [8], and γ rays from near-solar annihilations [9].

Dark matter neutralinos in the galaxy incident on the Sun can elastically scatter inside the Sun and become trapped in the solar gravitational well [10]. During numerous subsequent passages of neutralinos through the Sun, yet before becoming trapped inside the Sun, a small fraction of the neutralinos will annihilate outside the Sun where their annihilation products can escape. A calculation that followed the shrinking orbits predicted that the near-solar annihilation rate equaled 2×10^{20}, 2×10^{18}, and 4×10^{15} s^{-1} for neutralino masses of 0.35, 1.0, and 3.5 TeV, respectively, and that the radial annihilation distribution inside spherical shells of width dr outside the Sun a distance r from the Sun center equaled about $dN/dr = r^{-3}$ [9]. Most of the annihilation was found to occur within less than a solar radii of the solar surface, and the annihilation near stars was found to dominate the annihilation between stars. Uncertainties in local galactic dark matter density, the supersymmetric masses, and the neutralino composition limit the precision of the predictions.

II. PRODUCED SPECTRA

The lightest neutralino consists of an unknown mixture of the supersymmetric partners of the two neutral electroweak gauge bosons B and W_3 and two neutral Higgs bosons h^0. This analysis uses a pure Higgsino neutralino. The two dominant annihilation modes of two Higgsino neutralinos are to Z^0Z^0 or W^+W^- [11]. The initial produced particle energy spectrum generated from annihilation into Z^0Z^0 and W^+W^- is simulated by the Monte Carlo particle generator JETSET 7.4 [12], and the subsequent decay of produced particles into final electrons, positrons, and γ rays is simulated by the event generator GEANT 3.15 [13]. While the lower energy electrons are produced from the indirect decays of produced hadrons and muons, the highest energy electrons and positrons are produced predominantly from the leptonic decays of $Z^0\to e^+e^-$ and $W^\pm\to e^\pm\nu$ with branching fractions of 3% and 11%, respectively. The electron and positron spectra from both Z^0Z^0 and W^+W^- decays resemble each other except for an increased high energy electron and positron fluxes from the W^+W^- decays. The sum of the matching electron energy spectrum and positron energy spectrum, averaged over the Z^0Z^0 and W^+W^- modes assuming neutralino and chargino mass equality, will be used for this analysis for three neutralino masses, and is shown in Fig. 1. The γ-ray spectrum is produced primarily from the decay of neutral pions, and lacking the production from the direct decay of Z^0 and $W^\pm$, the γ-ray flux falls below the electron flux at the higher energies as seen in Fig. 1.

The electron spectrum can be modified by solar magnetic fields. Solar magnetic fields are complex, time-varying, and not well-measured. Kilogauss fields can be found in solar flares, and 100 G fields can be found near the photosphere in both closed loops and open lines [14]. To demonstrate the effect of solar magnetic fields on the electron spectrum, the solar magnetic fields are modeled by a simple dipole field with strength of 0.3 G at the solar equator, even though such a dipole field poorly represents the solar magnetic fields.

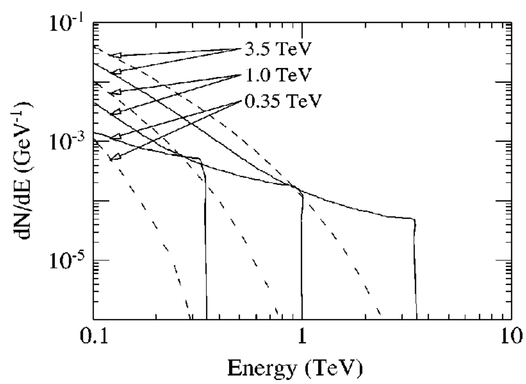

FIG. 1. The electron plus positron energy spectra from the decays of Z^0 and $W^\pm$ produced from the annihilation of 0.35, 1.0, and 3.5 TeV neutralinos are shown with solid lines. The γ-ray energy spectra from the decays of Z^0 and $W^\pm$ produced from the annihilation of the same energy neutralinos are shown with dashed lines.

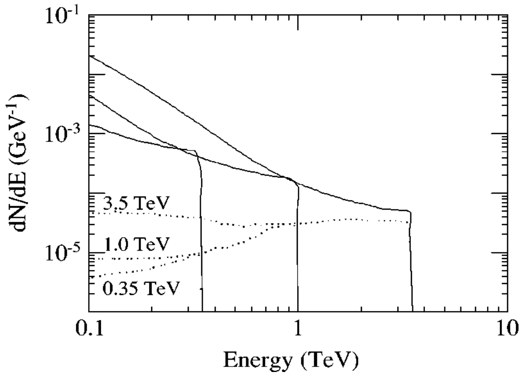

FIG. 2. The electron plus positron energy spectra from the decays of both Z^0 and $W^{\pm}$ produced from the annihilation of 0.35, 1.0, and 3.5 TeV neutralinos are shown with solid lines. The spectra subsequently modified by the effects of the simple dipole model of the solar magnetic fields are shown with dotted lines.

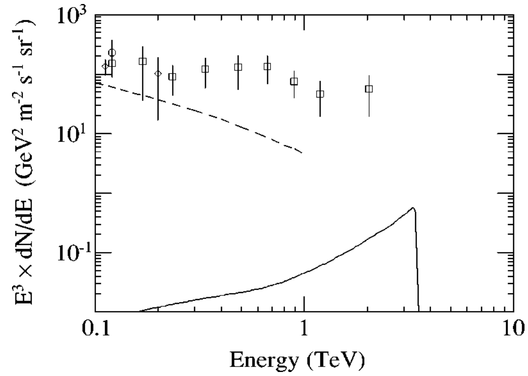

FIG. 3. The astrophysical electron energy spectrum measured by Nishimura *et al.* [22] is represented with squares, by Tang [19] with diamonds, and by Golden *et al.* [18] with an octagon. The spectrum predicted by Atoyan *et al.* [21] is shown by a dashed line. The electron plus positron energy spectrum produced from the decays of both Z^0 and $W^{\pm}$ produced from the annihilation of 3.5 TeV neutralinos scaled to accompany the mono-energetic 3.5 TeV γ-ray signal is shown with a solid line.

Electrons were created with random angles, random energies weighted by the JETSET, GEANT simulation, and random radii weighted by the radial annihilation distribution. While most electrons with energies above several TeV escape the solar magnetic fields, lower energy electrons travel helixially in the magnetic fields where they can be redirected toward the poles, strike the solar surface, or be trapped. The electron spectrum of escapees within 10° of the dipole field equator, corrected for solid angle, is shown in Fig. 2. In addition to modifying the escaping electron spectrum, solar flares can produce electrons and γ rays with energies below and beyond 1 GeV [15]. Solar flares produce particles following steep spectra such as $dN/dE = E^{-3.6}$ with time-varying fluxes [16], while the neutralino annihilations produce particles from hadronic decays following a flatter spectrum $dN/dE = E^{-1.2}$. Experimental measurements must consider that the observed near-solar electron signal and the solar-influenced background will vary in spatial size. The predictions will employ the electron spectrum unmodified by the solar magnetic fields. The predictions will account for the 20% loss of particles absorbed by the solar backside if the particles traveled straight.

III. OBSERVED SPECTRA

The astrophysical electron energy spectrum has been measured at energies up to 120 GeV by a balloon-borne superconducting magnetic spectrometer [17], to 200 GeV by a balloon-borne Čerenkov detector [18], and to 2 TeV by balloon-borne emulsion detectors [19]. The measured electron spectra shown in Fig. 3 are actually electron plus positron spectra since emulsion detectors and Čerenkov detectors do not distinguish the sign of the electric charge. The measured electron spectra assumed a flux uniform throughout the sky although uniformity of the electron spectrum throughout the sky has not been verified, and nor has been the uniformity over periods of time and throughout the galaxy. The dominant source of galactic electrons is thought to be supernova shock acceleration, after which the electrons experience partially entrapment in the galaxy and attenuation by interstellar magnetic fields [20]. The galactic electron energy spectrum has been predicted by various authors [19,21,22], one of which ([21]) is shown in Fig. 3. The measured astrophysical electron energy spectrum at energies above 500 GeV rises above the flux expected from the predicted galactic electron energy spectrum. The excess of measured flux over predicted flux has been attributed to the contribution of electrons from recent nearby sources which would have suffered less attenuation at higher energies [21,22]. The measured astrophysical electron spectrum shows no significant evidence for a near-solar-neutralino-produced electron spectrum component below 1 TeV, while above 1 TeV the predictions of the galactic electron spectrum are uncertain due to the parameter dependence of the modeling galactic propagation. Separating a contribution of electrons from near-stellar neutralino annihilation from a contribution of electrons from recent, nearby supernovas, especially considering the parameter dependence of modeling galactic propagation, would be difficult. Using the near-solar annihilation rates, and the produced electron spectra, the neutralino all-sky-averaged electron spectra are predicted to be $\langle f_{e^{\pm}} \rangle = 1 \times 10^{-12}$, 4×10^{-15}, and 3×10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1} at energies just below the neutralino masses of 0.35, 1.0, and 3.5 TeV, respectively, which all fall well below the measured electron spectrum. A greatly enhanced flux of dark matter from the galactic plane to the Sun or an enhanced ratio of that dark matter annihilating outside the Sun would be needed to produce a significant signal in the measured all-sky-averaged astrophysical electron spectrum.

The two dominant annihilation modes of two Higgsino neutralinos produce Z^0Z^0 or W^+W^- via t-channel exchange of a neutralino or a chargino respectively, with a low temperature annihilation cross section, assuming neutralino and chargino mass equality [23],

$$\langle \sigma v \rangle_{\tilde{h}^0 \tilde{h}^0} = \frac{\pi (2 \cos^4 \theta_w + 1) \alpha^2}{16 \sin^4 \theta_w \cos^4 \theta_w m_{\tilde{\chi}}^2} = 8 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \left(\frac{m_{\tilde{\chi}^0}}{1 \text{ TeV}} \right)^{-2}.$$

The annihilation cross section of pure B-ino neutralinos is predicted to be smaller. Another annihilation mode of neutralinos is the mode that produces, via $W^{\pm}$-chargino loops, two mono-energetic γ rays which offers a cleaner signature than the annihilation into a non-mono-energetic electron spectrum. A pure Higgsino neutralino with mass much greater than $m_{W^\pm}$ is predicted to be degenerate with the chargino and have neutralino-mass-independent cross section, in the low velocity limit, into a pair of mono-energetic γ rays [24]:

$$\langle \sigma v \rangle_{\tilde{h}^0 \tilde{h}^0 \to \gamma\gamma} = \frac{\pi \alpha^4}{4 \sin^4 \theta_W m_{W^\pm}^2} = 7 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1}.$$

Other authors have predicted a smaller cross section [25]. The annihilation cross section of pure B-ino neutralinos to a mono-energetic γ ray, via lepton-slepton or quark-squark loops, is predicted to be smaller [23]. If the total annihilation cross section for neutralinos is less sensitive to the neutralino composition than is the cross section for neutralino annihilation to mono-energetic γ rays, then measuring the electron signal and the mono-energetic γ-ray signal would constrain the neutralino composition. The theoretical uncertainties of supersymmetry preclude reliable predictions of the annihilation cross sections.

The most sensitive limits on near-solar γ rays available are provided by balloon-borne emulsion chamber detectors flown below an average atmospheric overburden of 5.5 g cm^{-2} where astrophysical γ rays would survive passage through air which has a radiation length of 37 g cm^{-2} [8]. The dominant background for γ-ray measurements consists of γ rays from π^0 produced by cosmic rays striking the atmosphere. A reported possible mono-energetic γ-ray signal, albeit with limited statistical significance, at 3.5 ± 0.3 TeV energy carried an all-sky-averaged mono-energetic γ-ray flux of $\langle f_\gamma \rangle = 2.0 \pm 1.0 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The electron measurement and γ-ray measurement had a relative factor of 2 between their exposures toward the Sun. The ratio of the two dominant annihilation cross sections to the mono-energetic γ-ray cross section for 3.5 TeV Higgsino neutralinos is predicted to be $\langle \sigma v \rangle_{Z^0 Z^0, W^+ W^-} / \langle \sigma v \rangle_{\gamma\gamma} = 78$. From these factors and the observed mono-energetic γ-ray flux $\langle f_\gamma \rangle$, the corresponding flux of electrons and positrons at 2 TeV is predicted to be $\langle f_{e^\pm} \rangle = 2 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$. The electron spectrum deduced for this flux is shown in Fig. 3. This flux falls below the measured electron spectrum at the highest measured energy of 2 TeV, which was measured to be [22] $\langle f_{e^\pm} \rangle = 7 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$.

A possible signature of neutralino annihilation is an increase in the flux of astrophysical positrons compared with the predicted flux of positrons produced by cosmic-ray interactions with the interstellar medium. An increase in the astrophysical positron versus electron ratio at energies of tens of GeV measured by two experiments [5] was not verified by a third experiment [6]. The strongest signal for the positron ratio due to neutralino annihilation would be found at energies just below the neutralino mass. Distinguishing positrons from electrons at energies above hundreds of GeV by a realizable satellite detector proves difficult.

IV. FLUX PREDICTIONS FOR FUTURE EXPERIMENTS

Millagro [26] is a water Čerenkov, air shower array which, unlike atmospheric Čerenkov telescopes, can observe electrons and γ rays from the Sun. MILAGRO consists of a water-filled, opaque-covered reservoir instrumented with three layers of phototubes in which the upper layer measures the electromagnetic shower component, the middle the hadronic component, and the lower the muonic component. The detector offers an angular resolution of 1°, a minimum energy threshold of 300 GeV, an energy resolution of $\pm 50\%$, and an energy-dependent effective area of $10 \ (E/\text{GeV}) \text{ m}^2$. Most of the electron and γ-ray fluxes from near-solar neutralino annihilation will fit inside the 1 square degree resolution. By rejecting hadron-rich showers, Milagro might achieve electron and γ-ray acceptances of near 100% and a hadronic cosmic-ray rejection of 90%. The background generated from showers induced by hadronic cosmic rays with flux $dN_h/dE = 1 \ (E/\text{TeV})^{-2.7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$ [27] will exceed the background from galactic electrons with flux $dN_{e^\pm}/dE = 1.6 (E/100 \text{ GeV})^{-3.3} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{GeV}^{-1}$ [20] which exceeds the background from galactic γ rays [28]. Near-solar Higgsino neutralino annihilation to electrons and γ rays with energies above 300 GeV can be predicted to provide a signal, compared with the off-source flux, with 5σ statistical significance in 8, 3×10^3, and 1×10^7 h of direct overhead solar exposure for neutralino masses of 0.35, 1.0, and 3.5 TeV, respectively. The background should be reduced further by the blockage of the solar disk on galactic cosmic rays. Milagro awaits commencement in 1999.

The Gamma-ray Large Area Space Telescope (GLAST) [29] is a proposed satellite detector which can distinguish incident γ rays from incident electrons. GLAST offers an energy resolution of 10%, an angular resolution of 0.1° an effective area for top-entering γ rays of 0.8 m^2, and an effective area for top-entering electrons of $(1.6 \text{ m})^2$. By rejecting hadron-like showers in its 10 radiation length vertical depth calorimeter of segmented CsI scintillators, GLAST could achieve a near 100% electron acceptance and a near 100% hadronic cosmic-ray rejection. The angular resolution of GLAST, being smaller than the angular size of the solar disk, allows GLAST to reject the higher energy galactic cosmic rays not blocked by the Sun while retaining the 20% fraction of near-solar annihilations that are produced before the solar disk. Near-solar Higgsino neutralino annihilation can be predicted to provide a signal with 5σ statistical significance to electrons with energies above 100 GeV in 1×10^2, 5×10^3, and 6×10^5 h of direct overhead solar exposure and to γ rays with energies above 100 GeV in 2×10^3, 2×10^4, and 1×10^6 h of direct overhead solar exposure for neutralino masses of 0.35, 1.0, and 3.5 TeV, respectively. GLAST could provide measurements of the near-solar annihilation radial distribution, the neutralino mass especially from mono-energetic γ rays, and constraints on the neutralino composition from the ratio of the continuum electron and γ-ray signals to the mono-energetic γ-ray signal. If the observed 3.5 TeV mono-energetic γ-ray signal [8] is real and originates from near-solar annihilation, both Milagro and GLAST should be able to detect the accompanying electron and continuum γ-ray signal with 5σ statistical significance in under 1 day of direct overhead solar exposure. GLAST awaits launch in perhaps 2005.

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