Prospects for Observing Near-Solar Supersymmetric Dark Matter Annihilations

Steven C. Strausz
Department of Physics, University of Washington, Box 351560, Seattle, WA 98195-1560, USA

Abstract

The rate of dark matter supersymmetric neutralinos captured in the solar system and annihilated near the Sun and the produced electron and γ ray energy spectra are calculated. This dark matter signal is shown to be suited to be observed by the Milagro air shower detector.

1 Introduction

A good candidate for a component of dark matter is the lightest supersymmetric particle such as the neutralino (for review see Jungman, Kamionkowski, & Griest 1996). The absence of supersymmetry at colliders sets a lower limit on the neutralino mass of about 80 GeV. The convergence of coupling constants suggests a neutralino mass between 100 GeV and 10 TeV (Amaldi *et al.* 1991). The cooling, annihilation, and freeze-out of supersymmetric particles in the early universe set upper limits on the neutralino mass of 3.2 TeV (Griest, Kamionkowski, & Turner 1990) or 7 TeV (Edsjö & Gondolo 1997).

Two neutralinos can annihilate into various particles. Observational limits have been set on the flux of galactic-neutralino-annihilation-produced positrons (Barbiellini *et al.* 1996; Barwick *et al.* 1995; Golden *et al.* 1996), antiprotons (Boezio *et al.* 1997), and mono-energetic γ rays (Strausz 1997).

A fraction of the galactic dark matter neutralinos intersecting the Sun will elastically scatter and become trapped in the solar system (Gaisser *et al.* 1986; Srednicki *et al.* 1987). After repeated passages through the Sun, most trapped neutralinos will thermalize inside the Sun and eventually annihilate. Observational limits on the flux of muon neutrinos produced from inner-solar neutralino annihilations have been reported by Kamioka (Mori *et al.* 1993) and IMB (LoSecco *et al.* 1987).

2 Near-Solar Annihilation

In addition to annihilations in the galaxy and inside the sun, neutralinos captured in the solar system can annihilate near the Sun. Rather than attempt to follow millions of neutralinos for millions of years as they orbit in the solar system, the orbits of neutralinos captured in the solar system with initially highly elliptical orbits will be approximated by one dimensional orbits through the center of the Sun with zero impact parameter (Strausz 1999a). Planetary perturbations to the neutralino orbits will be ignored. A local galactic dark matter density $\rho_{dm} = 0.3\,\mathrm{GeV\,cm^{-3}}$ consisting solely of neutralinos will be used for this analysis. The rate of neutralinos intersecting the solar disk is $R_\odot = 4\pi r_\odot^2 v_{gal}\rho_{dm}/m_{\tilde{\chi}^0} = 1\times 10^{26}\,\mathrm{s^{-1}}(m_{\tilde{\chi}^0}/1\,\mathrm{TeV})^{-1}$. The solar central escape to infinity velocity $v_{c\infty} = 1385\,\mathrm{km\,s^{-1}}$ exceeds the typical galactic rotation velocity $v_{gal} = 220\,\mathrm{km\,s^{-1}}$ and provides a deep gravitational well of which a significant fraction lies near yet outside the solar surface.

The probability that a neutralino will elastically scatter with a hydrogen nucleus during one passage through the solar diameter is $P = 2r_\odot\sigma_{\tilde{\chi}^0 p}\rho_\odot/m_p = 0.12(\sigma_{\tilde{\chi}^0}/10^{-36}\,\mathrm{cm^2})$. Other elastic scattering cross sections have been proposed (Primack *et al.* 1988). After a 1-dimensional head-on collision with a proton, the neutralino loses an average velocity of $\delta v = v2m_p/m_{\tilde{\chi}^0}$.

Of the neutralinos that elastically scatter in the Sun, only a small fraction will become captured in the solar system. The fraction of incoming neutralinos slow enough to be capturable occupies the low velocity portion of the local galactic dark matter Maxwell-Boltzmann distribution $F_{MB}(v)$, with average velocity equal the galactic velocity, $f_c = \int_0^{v_{c\infty}\sqrt{4m_p/m_{\tilde{\chi}^0}}} dv\, F_{MB}(v)$ which equals 0.2, 0.06, 0.009 for neutralino masses of 0.35, 1.0, 3.5 TeV, respectively.

From the neutralino solar-incidence rate, the fraction of neutralinos slow enough to be captured, and the neutralino scattering probability, the neutralino solar capture rate is determined $R_c = R_\odot f_c P$ which equals 7×10^{24}, 7×10^{23}, $3 \times 10^{22}\,\mathrm{s}^{-1}(\sigma_{\tilde{\chi}^0 p}/10^{-36}\,\mathrm{cm}^2)$ for neutralino masses of 0.35, 1.0, 3.5 TeV, respectively. By comparison, this solar capture rate is smaller than that from another computation (Mori *et al.* 1993) of 2×10^{25}, 2×10^{24}, $2 \times 10^{23}\,\mathrm{s}^{-1}$ using the same elastic scattering cross section.

From the probability of scattering during solar passage, and the average neutralino velocity assumed to equal the solar central escape to surface velocity $v = v_{cs}$ the average velocity loss per solar passage is determined $\Delta v = P v_{cs} 2 m_p / m_{\tilde{\chi}^0} = 0.14\,\mathrm{km\,s}^{-1}(m_{\tilde{\chi}^0}/1\,\mathrm{TeV})^{-1}(\sigma_{\tilde{\chi}^0 p}/10^{-36}\,\mathrm{cm}^2)$ indicating that a massive neutralino passes through the sun many times before total solar entrapment.

The neutralino density $\rho_1(r)$ created by 1-dimensional 1-particle orbits is numerically computed from a summation of densities from shrinking orbits whose maximum radii are determined from the repeated velocity loss Δv. The complete 3-dimensional density near the Sun is determined from the 1-dimensional 1-particle density and the neutralino solar capture rate $\rho_3(r) = \rho_1(r) m_{\tilde{\chi}^0} R_c/(4\pi r^2)$.

The lightest neutralino consists of an unknown mixture of the supersymmetric partners of the neutral electroweak gauge bosons and the neutral Higgs bosons. A pure Higgsino neutralino will be used for this analysis. The two dominant annihilation modes of two Higgsino neutralinos are into $Z^0 Z^0$ and into $W^+ W^-$, via a *t*-channel exchange of neutralino and chargino, respectively, with annihilation cross section in the low velocity limit predicted to be (Griest, Kamionkowski, & Turner 1990) $\langle \sigma v \rangle_{\tilde{\chi}^0 \tilde{\chi}^0} = \pi (2 \cos^4 \theta_W + 1) \alpha^2 / (16 \sin^4 \theta_W \cos^4 \theta_W m_{\tilde{\chi}}^2) = 8 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}(m_{\tilde{\chi}^0}/1\,\mathrm{TeV})^{-2}$.

The near-solar annihilation rates for Higgsino neutralinos $R_{>r_\odot} = \int_{>r_\odot} d^3 r\,(\rho_3(r)/m_{\tilde{m}_{\chi}^0})^2 \langle \sigma v \rangle_{\tilde{h}^0 \tilde{h}^0}$ equal 2×10^{20}, 2×10^{18}, $4 \times 10^{15}\,s^{-1}$ for neutralino masses of 0.35, 1.0, 3.5 TeV, respectively, which are small fractions of the solar-capture rates. While the inner-solar annihilation rate is found to be independent of neutralino annihilation cross section, the near-solar annihilation rate is found to be independent of neutralino elastic scattering cross section.

3 Produced γ Rays and Electrons

An interesting annihilation mode for two Higgsino neutralinos that offers a particularly clean signature is to two mono-energetic γ rays, via a chargino-$W^\pm$ loop, with annihilation cross section in the low velocity limit predicted to be (Bern, Gondolo, & Perelstein 1997) $\langle \sigma v \rangle_{\tilde{\chi}^0 \tilde{\chi}^0 \to \gamma\gamma} = \pi \alpha^2 / (4 \sin^4 \theta_W m_{\tilde{\chi}}^2) = 7 \times 10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}(m_{\tilde{\chi}^0}/1\,\mathrm{TeV})^{-2}$. Another smaller mono-energetic γ-ray cross section has been proposed (Bergström & Kaplan 1994) Since γ rays are unperturbed by solar and terrestrial magnetic fields, near-solar γ rays should provide a sharp angular signal.

The smooth galactic halo model of dark matter distribution proposes a dark matter density in the galaxy of $\rho(d) = \rho_{dm}(d_c^2 + d_\odot^2)/(d_c^2 + d^2)$ with solar distance $d_\odot = 8.5\,\mathrm{kpc}$ and core radius $d_c = 2\,\mathrm{kpc}$. The smooth galactic halo dark matter distribution predicts that the neutralino annihilations along line of sight through the galactic center $f_\gamma = 2(4\pi\,\mathrm{sr})^{-1} \int_0^\infty dx\,(\rho(d)/m_{\tilde{m}_{\chi}^0})^2 \langle \sigma v \rangle_{\tilde{h}^0 \tilde{h}^0} = 1 \times 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, for $3.5\,\mathrm{TeV}$ neutralino mass, will be less than the γ-ray flux from near-solar neutralino annihilation from the same mass neutralinos viewed from earth averaged over 1 square degree, predicted to be $f_\gamma = 2(4\pi d_\oplus^2 \Omega)^{-1} \int_{>r_\odot} d^3 r\,(\rho(d)/m_{\tilde{m}_{\chi}^0})^2 \langle \sigma v \rangle_{\tilde{h}^0 \tilde{h}^0} = 1 \times 10^{-9}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. Compared with a diffuse galactic source, the near-solar source offers the additional advantage of a localized on-source minus off-source signal detection.

The two dominant annihilation modes of two Higgsino neutralinos into $Z^0 Z^0$ and into $W^+ W^-$ produce, via decays, a broad energy spectrum of particles including electrons, positrons, and γ rays. The initial produced particle spectrum is simulated by the particle generator JETSET 7.4 (Sjöstrand 1994), and the subsequent decay of produced particles into final electrons, positrons, and γ rays is simulated by the event generator GEANT 3.15. Two decay modes of particular interest are the leptonic decays of $Z^0 \rightarrow e^+e^-$ and $W^\pm \rightarrow e^\pm\nu$ with branching fractions 3% and 11%, respectively. The electron and positron energy spectrum flattens at high energies and sharply cuts-off at the neutralino mass as seen in Figure 1 (Strausz 1999b). This electron and positron flat energy spectrum followed by a sharp cut-off offers a good signal compared with the background cosmic-ray spectrum of $dN/dE = E^{-2.7}$. Unlike the nearby near-solar source, electrons and positrons produced in the galaxy suffer angular deflections from the galactic magnetic fields thereby losing their original directions and suffer energetic attenuation from synchrotron radiation with the galactic magnetic fields, especially above TeV energies (Nishimura *et al.* 1980; Atoyan, Aharonian & Völk 1995) thereby losing their sharp cut-off spectrum at the neutralino mass. Hence, electrons and positrons produced in the galaxy from neutralino annihilation may be difficult to distinguish from electrons and positrons produced in the galaxy by supernovas and cosmic ray interactions. An observed near-solar electron and positron signal will be complicated by deflection in the solar magnetic fields which are complex, time-varying, and not well measured. The TeV electrons will suffer less angular deflection and hence less angular smearing of the signal than lower energy electrons. Even though high energy electrons and positron represent a small decay fraction of their annihilation mode, their larger neutralino annihilation cross section might provide a larger signal than the smaller annihilation cross section for mono-energetic γ rays. For a detector with limited energy resolution, such as $\pm 50\%$, which will be unable to take full advantage of the narrow $\pm 0.1\%$ energy width of the mono-energetic γ-ray signal, the sharp cut-off of the electron and positron energy spectrum, compared with a $dN/dE = E^{-2.7}$ background, might provide as good a signal of the supersymmetric mass as the mono-energetic γ ray signal.

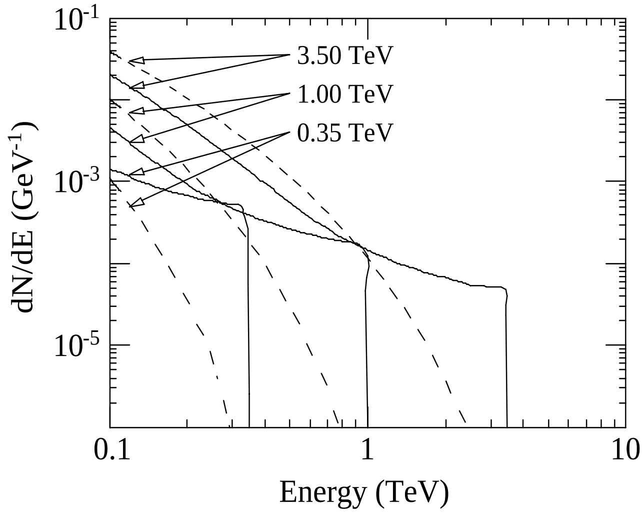

Figure 1: The electron plus positron energy spectrum from the decays of Z^0 and $W^\pm$ produced from the annihilation of 0.35, 1.0, 3.5 TeV neutralinos are shown with solid lines. The γ-ray spectra from the decays of Z^0 and $W^\pm$ produced from the annihilation of the same mass neutralinos are shown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

4 Milagro Predictions

Typical extensive cosmic ray air shower array detectors have energy thresholds too high to detect the neutralino TeV annihilation products. Atmospheric Čerenkov telescopes cannot observe near-solar signals. Satellite γ-ray detectors offer only small areas. Near-solar TeV γ rays and electrons are suited for detection by Milagro. Milagro (Yodh 1997) is a light-tight, water-filled reservoir instrumented with phototubes sensitive to atmospheric showers with an angular resolution of 0.3 degrees, a hadronic shower rejection of 50%, an electromagnetic shower acceptance of 100%, a minimum energy threshold of 300 GeV, an energy resolution of $\pm 50\%$ above a TeV, and an energy-dependent effective area of $10(E/\mathrm{GeV})\ \mathrm{m}^2$. The background will be dominated by cosmic-ray protons with flux $dN/dE = 1.(E/\mathrm{TeV})^{-2.7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$ (Burnett *et al.* 1990). For a one square degree angle observed around the Sun, Milagro can be predicted to provide a 5 σ statistical significance near-solar neutralino annihilation signal to electrons and continuum γ rays above 300 GeV energy in 10, 10^4, 10^7 hours of overhead Sun for neutralino masses of 0.35, 1.0, 3.5 TeV, respectively, while the mono-energetic γ-ray signal in a $\pm 50\%$ energy region requires 10, 10^2, 10^4 hours of overhead Sun, for the respective neutralino masses, to achieve a 5 σ statistical significance. The actual time required to measure a significant signal will depend on the experimental response of Milagro and the extent of the solar magnetic field smearing on the near-solar signal and the solar shadowing of galactic cosmic rays. Milagro is scheduled to commence full operation in 1999.

Acknowledgements

The author is indebted to Todd Haines for useful discussions.

References

Amaldi, U. et al. 1991, Phys. Lett. B 260, 447
Atoyan, A.M., Aharonian, F.A., & Völk, H.J. 1995, Phys. Rev. D 52, 3265
Barbiellini, G. *et al.* 1996, A&A 309, L15
Barwick, S.W. *et al.* 1995, Phys. Rev. Lett. 75, 390
Bergström, L. & Kaplan, J. 1994, Astrop. Phys. 2, 261
Bern, Z., Gondolo, P., & Perelstein., M. 1997, Phys. Lett. B 411, 86
Boezio, M. *et al.* 1997, ApJ 487, 415
Burnett, T.H. *et al.* 1990, ApJ 349, L25
Edsjö, J. & Gondolo, P. 1997, Phys. Rev. D 56, 1979
Gaisser, T. *et al.* 1986, Phys. Rev. D 34, 2206
Golden, R.L. *et al.* 1996, ApJ 457, L107
Griest, K., Kamionkowski, M., & Turner, M.S. 1990, Phys. Rev. D 41, 3565
Jungman, G., Kamionkowski, M., & Griest, K. 1996, Phys. Rep. 267, 195
LoSecco, J.M. *et al.*, 1987, Phys. Lett. B 188, 388
Mori, M., *et al.* 1993, Phys. Rev. D 48, 5505
Nishimura, J. *et al.* 1980, ApJ 238, 394
Primack, J.R. *et al.* 1988, Ann. Rev. Nucl. Part. Sci. 38, 751
Silk, J., Olive, K., & Srednicki, M. 1985, Phys. Rev. Lett. 55, 257
Sjöstrand, T. 1994, Comp. Phys. Comm. 82, 74
Srednicki, M. *et al.* 1987, Nucl. Phys. B 279, 804
Strausz, S.C. 1997, Phys. Rev. D 55, 4566
Strausz, S.C. 1999a, Phys. Rev. D 59, 023504
Strausz, S.C. 1999b, Phys. Rev. D accepted
Yodh, G. for Milagro Collaboration 1997, Towards a Major Atmospheric Čereknov Detector: 5th Workshop of TeV Gamma Ray Astrophysics, Kruger National Park, South Africa, edited by O. C. de Jager (Potchefstroom, South Africa: Westprint)