Near-solar supersymmetric dark matter annihilations

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The annihilation rate of supersymmetric dark matter trapped in the solar gravitational well, yet outside the Sun, is calculated. Though the fraction of annihilations near the Sun is found to be small compared with annihilations inside the Sun, the resultant flux of mono-energetic γ rays at Earth from the near-solar source is found to be brighter than that from the galactic source. Comparisons are made with previous and future experiments. [S0556-2821(98)08224-1]

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I. INTRODUCTION

A candidate for dark matter is the cosmological relic, lightest supersymmetric particle, such as the neutralino $\tilde{\chi}^0$ [1]. The absence of supersymmetry at electron-positron collisions sets a lower limit on the neutralino mass of about 80 GeV. A recent study of supersymmetric particles in the early universe set a upper limit on the neutralino mass of 7 TeV [2].

Some of the dark matter neutralinos intersecting the Sun will elastically scatter and lose sufficient energy to become trapped in the solar gravitational well [3]. On subsequent orbits through the Sun, more energy will be lost until neutralinos fall to the center of the Sun. An equilibrium is reached so that the annihilation rate equals the capture rate. All products from neutralino annihilations inside the Sun are absorbed by the sun except for neutrinos. The Kamiokande underground neutrino detector has used the predicted enhancement of neutralino annihilation inside the Sun [4] to set limits on dark matter [5].

A clean experimental signature of the annihilation of two neutralinos are annihilation modes creating mono-energetic γ rays [6]. The predicted γ-ray flux from dark matter neutralinos in the galactic center has been calculated [7]. Another possible source for neutralino annihilations is near the Sun.

II. NEAR-SOLAR NEUTRALINO ANNIHILATION

Most models proposed for the dark matter distribution assume a rotational galactic velocity $v_{gal}=220\ \mathrm{km\ s^{-1}}$ and a galactic spherically symmetric dark matter density distribution with a local mass density $\rho_{dm}=0.3\ \mathrm{GeV\ cm^{-3}}$ [8], and a Maxwell-Boltzmann velocity distribution. Though the composition of dark matter is unknown, dark matter will be assumed to consist purely of neutralinos. The neutralino solar-incidence rate through an solar-sized area is

$$R_{\odot}=v_{gal}\left(\frac{\rho_{dm}}{m_{\tilde{\chi}^0}}\right)4\pi r_{\odot}^2=1\times10^{26}\ \ \mathrm{s}^{-1}\left(\frac{m_{\tilde{\chi}^0}}{1\ \ \mathrm{TeV}}\right)^{-1}.$$

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 offers dark matter a deep gravitational well of which a significant fraction lies outside the Sun.

Neutralinos initially intersect the Sun with random impact parameters, and the captured neutralinos will follow two-dimensional, highly eccentric, sun-intersecting orbits. For this calculation, the orbits will be simplified to 1-dimensional linear orbits through the solar center with zero impact parameter.

The probability that a neutralino will elastically scatter with a hydrogen nucleus during one passage through the solar diameter is

$$P=2r_{\odot}\sigma_{\tilde{\chi}^0p}\frac{\rho_{\odot}}{m_p}=0.12\left(\frac{\sigma_{\tilde{\chi}^0}}{10^{-36}\quad\mathrm{cm}^2}\right).$$

A neutralino-hydrogen elastic scattering cross section of $\sigma_{\tilde{\chi}^0p}=10^{-36}\ \ \mathrm{cm}^2$ will be used [9]. Other authors have predicted smaller elastic scattering cross sections [10]. For the near-solar annihilation rate, errors introduced by approximations that increase the neutralino solar capture rate will, in general, decrease the number of near-solar orbits before complete solar entrapment, and tend to cancel. In particular, the near-solar annihilation rate is found to be independent of elastic scattering cross section. After a 1-dimensional head-on scattering between a massive neutralino with proton, the neutralino loses an average velocity of $\delta v=v2m_p/m_{\tilde{\chi}^0}$.

Of the neutralinos that accelerate into the Sun and elastically scatter, only a small fraction will lack the velocity necessary to escape the solar gravitational well. The fraction of galactic neutralinos slow enough to be susceptible to capture by elastic scattering in the solar gravitational well occupies the low velocity portion of the local galactic dark matter Maxwell-Boltzmann velocity distribution $F_{MB}(v)$ whose average velocity is assumed to equal the galactic velocity v_{gal}

$$f_c=\int_0^{v_{c\infty}\sqrt{4m_p/m_{\tilde{\chi}^0}}}dvF_{MB}(v)$$

which equals 0.2, 0.06, 0.009 for 0.35, 1.0, 3.5 TeV respectively.

From the neutralino solar-incidence rate, the fraction of scattering neutralinos slow enough to be trapped, and the scattering probability, the neutralino solar capture rate is determined $R_c = R_\odot f_c P$ which equals 7×10^{24}, 7×10^{23}, 3×10^{22} $\mathrm{s}^{-1}(\sigma_{\tilde\chi^0 p}/10^{-36}\ \mathrm{cm}^2)$ for 0.35, 1.0, 3.5 TeV respectively. This neutralino solar capture rate will be used, and not a larger neutralino solar capture rate used by other authors [5].

The lightest neutralino consists of an unknown mixture of the supersymmetric partners of the B, W_3, and the neutral Higgs boson. The neutralino annihilation cross sections depend on the neutralino composition and unknown supersymmetric masses [11]. A pure Higgsino neutralino will be used for this calculation. The two dominant annihilation modes of two pure Higgsino neutralinos are predicted to be into W^+W^-, via t-channel exchange of $\tilde\chi^\pm$, and into Z^0Z^0, via t-channel exchange of $\tilde\chi^0$, with annihilation cross section in the low velocity limit, assuming supersymmetric mass degeneracy [12],

$$\langle\sigma v\rangle_{\tilde h^0\tilde h^0} = \frac{\pi(2\cos^4\theta_w+1)\alpha^2}{16\sin^4\theta_w\cos^4\theta_w m_{\tilde\chi}^2} = 8\times10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}\left(\frac{m_{\tilde\chi^0}}{1\ \mathrm{TeV}}\right)^{-2}.$$

The total Higgsino annihilation cross section will be assumed to equal the sum of Higgsino annihilation to W^+W^- and Z^0Z^0. Pure B-ino neutralinos are predicted to have a smaller annihilation cross section [12].

For comparison, the pure Higgsino neutralino annihilation rate between nearby stars with typical 4 ly interstellar separation and local dark matter density,

$$R_\star = \int d^3r\left(\frac{\rho_{dm}}{m_{\tilde\chi^0}}\right)^2\langle\sigma v\rangle_{\tilde h^0\tilde h^0} = 4\times10^{22}\ \mathrm{s}^{-1}\left(\frac{m_{\tilde\chi^0}}{1\ \mathrm{TeV}}\right)^{-4}$$

is less than the neutralino solar capture rate.

After neutralinos fall into the sun and thermalize with the Sun central temperature $T_\odot = 16$ MK [13], they acquire an average thermal velocity $v_T = \sqrt{3kT/m_{\tilde\chi^0}} = 19\ \mathrm{km\,s^{-1}}(m_{\tilde\chi^0}/1\ \mathrm{TeV})^{-1/2}$, significantly less than solar central escape to surface velocity $v_{cs} = 1240\ \mathrm{km\,s^{-1}}$. The thermalized neutralinos in their central core contribute an insignificant amount to the solar mass. Since thermalized neutralinos are trapped deep inside the Sun, annihilations outside the sun must occur before the neutralinos thermalize.

The probability of scattering during solar passage, and the average neutralino velocity for all scatterings assumed to equal the solar central escape to surface velocity $v = v_{cs}$ determine the average velocity loss per solar passage

$$\Delta v = P v_{cs} 2\frac{m_p}{m_{\tilde\chi^0}} = 0.14\ \mathrm{km\ s^{-1}}\left(\frac{m_{\tilde\chi^0}}{1\ \mathrm{TeV}}\right)^{-1}\left(\frac{\sigma_{\tilde\chi^0}}{10^{-36}\ \mathrm{cm}^2}\right)$$

indicating that a massive neutralino travels many solar passages before complete solar entrapment.

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

The 1 TeV pure Higgsino neutralino near-solar annihilation rate for orbits within 100 $\mathrm{R}_\odot$

$$R_{>r_\odot} = \int_{>r_\odot} d^3r\left(\frac{\rho_3(r)}{m_{\tilde\chi^0}}\right)^2\langle\sigma v\rangle_{\tilde h^0\tilde h^0} = 2\times10^{18}\ \mathrm{s}^{-1}$$

is a small fraction of the neutralino solar capture rate. Most of the near-solar annihilation occurs within one solar radius of the solar surface. Though the neutralino annihilation rate inside the sun exceeds the neutralino annihilation rate between suns, the neutralino annihilation rate near suns contributes only a tiny amount to the neutralino annihilation rate between suns.

III. ANNIHILATION INTO MONO-ENERGETIC γ RAYS

Higgsino neutralinos have annihilation modes, via $W^\pm$-chargino loops, into two mono-energetic γ rays. A pure Higgsino neutralino with mass much greater than m_W is predicted to be degenerate with the chargino and have a neutralino-mass-independent annihilation cross section in the low velocity limit into a pair of mono-energetic γ rays [14]

$$\langle\sigma v\rangle_{\tilde h^0\tilde h^0\to\gamma\gamma} = \frac{\pi\alpha^4}{4\sin^4\theta_W m_W^2} = 7\times10^{-29}\ \mathrm{cm}^3\ \mathrm{s}^{-1}.$$

Other authors have predicted a smaller cross section [15]. Pure B-ino neutralinos are predicted to have a smaller cross section for annihilations, via lepton-slepton or quark-squark loops, into two mono-energetic γ rays [12]

$$\langle\sigma v\rangle_{\tilde B\tilde B\to\gamma\gamma} = 4\times10^{-29}\ \mathrm{cm}^3\ \mathrm{s}^{-1}\left(\frac{m_{\tilde\chi^0}}{1\ \mathrm{TeV}}\right)^{-2}\left(\frac{m_{\tilde\chi^0}}{m_{\tilde f}}\right)^4$$

with sfermion mass $m_{\tilde f}$ greater than neutralino mass $m_{\tilde\chi^0}$ by an unknown amount. The theoretical uncertainties of supersymmetry preclude reliable predictions of the annihilation cross sections. The mono-energetic γ-ray annihilation mode produces a narrow signal with fractional energy width $\Delta E/E = v/c = 10^{-3}$.

A near-solar 3.5 TeV pure Higgsino annihilation source predicts a sky-averaged mono-energetic γ-ray flux at earth, including a factor of 2 for the γ-ray production in pairs and ignoring the 20% absorption of γ rays from the solar backside

$$\langle f_\gamma\rangle = \frac{2}{4\pi d_\oplus^2}\frac{1}{4\pi\mathrm{sr}}\int_{>r_\odot} d^3r\left(\frac{\rho_3(r)}{m_{\tilde\chi^0}}\right)^2\langle\sigma v\rangle_{\tilde h^0\tilde h^0\to\gamma\gamma} = 2\times10^{-14}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

which is larger than the predicted signal from neutralino annihilation in the galactic halo [7]. The most sensitive measured limits of near-solar γ rays over the 100 GeV to 10 TeV energy range are found by balloon-borne emulsion detectors flown below an average atmospheric overburden of 5.5 $\mathrm{g\,cm^{-2}}$ where astrophysical γ rays would survive passage through the air which has a radiation length of 37 g cm^{-2}. The dominant background for γ-ray measurements consisted 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 a sky-averaged mono-energetic γ-ray flux $\langle f_\gamma\rangle = 2.0\pm1.0\times10^{-9}$ $cm^{-2}\,s^{-1}\,sr^{-1}$ [16], which exceeds the near-solar Higgsino annihilation prediction. When the same γ-ray spectrum is used as an upper limit, any mono-energetic γ-ray signal from the 100 GeV to 10 TeV energy range must also fall below the near-solar Higgsino annihilation prediction. A neutralino solar capture rate used by other authors [5] which is 10 times larger will predict a 100 times larger near-solar annihilation rate, still below the present measured limits.

Employing the neutralino solar capture rate R_c, the Higgsino annihilation cross section $\langle\sigma v\rangle_{\tilde{h}^0\tilde{h}^0}$, and the cross section for Higgsino annihilation to γ rays $\langle\sigma v\rangle_{\tilde{h}^0\tilde{h}^0\to\gamma\gamma}$, to account for a sky-averaged mono-energetic γ-ray flux of 2.0×10^{-9} $cm^{-2}\,s^{-1}\,sr^{-1}$ the fraction of solar-captured neutralinos that annihilate outside the sun would need to equal about 5%.

The smooth halo model with core distance $d_c = 2$ kpc and distance of sun to galactic center $d_\odot = 8.5$ kpc proposes a dark matter density in galaxy $\rho(d) = \rho_{dm}(d_c^2 + d_\odot^2)/(d_c^2 + d^2)$ which predicts a γ-ray flux from the galactic center for 3.5 TeV neutralinos along line of sight

$$f_\gamma = \frac{2}{4\pi \mathrm{sr}} \int_0^\infty dx \left(\frac{\rho(d)}{m_{\tilde{\chi}^0}}\right)^2 \langle\sigma v\rangle_{\tilde{h}^0\tilde{h}^0\to\gamma\gamma}$$
$$= 1\times10^{-13}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$$

which is less than the predicted γ-ray flux from the Sun from near-solar neutralino annihilation at same neutralino mass $f_\gamma = 1\times10^{-9}$ $cm^{-2}\,s^{-1}\,sr^{-1}$.

The balloon-borne emulsion detectors provided only a limited exposure and lacked sky angle orientation. The Energetic Gamma Ray Experiment Telescope (EGRET) detector on-board the Compton satellite cannot measure energies about 50 GeV. Traditional air-shower arrays cannot detect showers with energies below hundreds of TeV. Atmospheric Čerenkov telescopes dare not face sunward. The Gamma-Ray Large Area Space Telescope (GLAST) satellite awaits launch early in the next century [17].

A detector capable of studying the near-solar neutralino annihilation γ-ray signal is Milagro [18]. Milagro is a water Čerenkov air-shower detector consisting of a water-filled reservoir, located at 36 degrees north latitude, covered with a light-tight barrier, and instrumented with photo-tubes. The detector offers a 1 sr angular acceptance, a 1 square degree angular resolution, and a lower energy threshold of a few hundred GeV. Milagro provides energy-dependent effective area of 3×10^3, 1×10^4, 4×10^4 m^2 for 0.35, 1.0, 3.5 TeV, respectively. In a summer of midday sun, Milagro can accumulate a solar exposure of 10^6 s. The dominant background for Milagro γ-ray measurements will consist of hadronic cosmic-ray-induced air-showers misidentified as γ-ray-induced air-showers. Cosmic rays are dominated by protons which follow the measured energy spectrum [19] $dN_p/dE = 0.1\ (E/\mathrm{TeV})^{-2.8}\ (\mathrm{m^2\ s\ sr\ TeV})^{-1}$. During that solar exposure, a 90% hadronic rejection ratio, a $\pm50\%$ energy resolution, and the assumption that an incident proton will create a detected shower equal in energy to an incident γ ray, the number of background showers acquired will equal 6×10^4, 3×10^4, 1×10^3 for 0.35, 1.0, 3.5 TeV, respectively. The γ-ray flux from the near-solar neutralino annihilation within one solar radius of the solar surface which fits inside the 1 square degree aperture,

$$f_\gamma = \frac{2}{4\pi d_\oplus^2} \int_{r_\odot}^{2r_\odot} d^3r \left(\frac{\rho_3(r)}{m_{\tilde{\chi}^0}}\right)^2 \langle\sigma v\rangle_{\tilde{h}^0\tilde{h}^0\to\gamma\gamma}$$

for a 100% γ-ray acceptance and similar solar exposure predicts the number of acquired signal γ rays will equal 4×10^3, 9×10^2, 1×10^2 for 0.35, 1.0, 3.5 TeV, respectively, equivalent to a 16, 5, 0.8 σ signal compared with background. The γ-ray flux for B-ino neutralinos will be smaller. The Milagro detector is scheduled to begin full operation in late 1998.

IV. DISCUSSION

The near-solar enhancement of supersymmetric dark matter can provide a bright detectable γ-ray signal. A measurable signal or limit on near-solar γ rays can constrain unknown parameters of supersymmetry and dark matter.

A careful computer simulation following the decaying 3-dimensional orbits with detailed elastic scatterings and planetary perturbations could provide a more definitive near-solar neutralino density distribution and annihilation rate.

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