Neutrino-induced Muon Fluxes from Neutralino Annihilations in the Sun and in the Earth

J. Edsjö

The flux of neutrino-induced muons at the surface of the Earth is calculated from injection of neutralino annihilation products in the core of the Sun and the Earth. An improved treatment of neutrino propagation through the Sun is performed and the results are presented in an easy-to-use parameterization. For an explicit supersymmetric model, an observable neutralino annihilation signal is demonstrated.

1. Introduction

The dark matter in the Universe may be constituted by the neutralino, which probably is the lightest supersymmetric particle. If these particles exist they will get trapped gravitationally by the Earth and the Sun where they can annihilate and produce other particles, e.g. fermion–antifermion pairs, gauge bosons and Higgs bosons. These particles can hadronise and/or decay producing high energy muon neutrinos which can be detected in neutrino detectors, in which the neutrinos produce muons via charged current interactions and the muons can be detected due to the Čerenkov light they emit.

We have considered the whole chain of processes from the annihilation products in the core of the Sun or the Earth to detectable muons at the surface of the Earth, see [1] for details. The neutrino flux at the surface of the Earth has been calculated earlier by others, e.g. [2–4], but in this calculation the neutrino propagation through the Sun has been considered more carefully and the neutrino interactions near the detector have been simulated to get the muon fluxes.

The hadronisation and/or decay of the annihilation products have been simulated with JETSET 7.3 [3] and the neutrino interactions on the way out of the Sun have been simulated with PYTHIA 5.6 [3]. The neutrino interactions near the detector (in which the detectable muons are produced) have also been simulated with PYTHIA 5.6.

2. Annihilation channels and interactions of annihilation products

A pair of neutralinos can annihilate to produce a fermion-antifermion pair or gauge bosons, Higgs bosons and gluons, i.e. $\tilde{\chi}\tilde{\chi} \rightarrow \ell^+\ell^-, q\bar{q}, gg, qgq, W^+W^-, Z^0Z^0, Z^0H^0, W^\pm H^\mp, H^0H^0$. These annihilation products will hadronise and/or decay, eventually producing high energy muon neutrinos. Since the density in the core of the Sun and the Earth is high, the possibility of interactions of the annihilation products with the surrounding medium must be considered.

In agreement with earlier work [2], we find that light hadrons and muons get stopped well before they have time to decay both in the Sun and in the Earth. Tau leptons lose hardly any energy at all and their interactions can to a good approximation be neglected. Gauge bosons, Higgs bosons and top quarks also decay long before interacting. The gluon channels do not give rise to any significant high energy muon neutrino fluxes, and can thus be neglected. The branching ratio to neutrinos directly is close to zero for slow neutralinos annihilating and these channels do thus not contribute. However, the heavy hadrons ($B$’s, $D$’s, $\Lambda_b$’s etc) may or may not interact and their interactions can not be neglected and they can not be considered to be stopped completely either.

For the heavy hadrons we simulate the hadronisation as if the surrounding medium were not present. Afterwards we estimate how many times the heavy hadrons have interacted and how much energy they have lost in each interaction. The
The neutrino spectrum ($\nu_\mu + \bar{\nu}_\mu$) at the surface of the Sun from injection of 500 GeV neutrinos and anti-neutrinos in the core of the Sun with the method of Ritz and Seckel [2] and with the new method. 

The neutrino spectrum ($\nu_\mu + \bar{\nu}_\mu$) weighted by $E_\nu^2$ at the surface of the Sun for the $W^+W^-$-channel with a neutralino mass of 500 GeV. The two peaks in the Ritz and Seckel spectra correspond to $\nu_\mu$ and $\bar{\nu}_\mu$ respectively. 

The Higgs bosons decay to ordinary particles and the muon neutrino flux they produce can be calculated from the flux that their decay products produce [1]. For the top quark, only the standard model decay $t \rightarrow W^+b$ has been considered. In supersymmetry, the decay mode $t \rightarrow H^+b$ is open if the $H^+$ mass is light enough, and the flux from this decay mode can be calculated from the fluxes of the $b$ quark and the decay products of the $H^+$. 

### 3. Neutrino interactions

The produced muon neutrinos can interact on their way out of the Sun or the Earth. The total neutrino-nucleon cross section is given approximately by $\sigma_{CC} = a(E_\nu/\text{GeV}) \times 10^{-39}$ cm$^2$ and $\sigma_{NC} = b(E_\nu/\text{GeV}) \times 10^{-39}$ cm$^2$ for charged and neutral currents respectively. We have calculated the coefficients $a$ and $b$ using the new GRV structure functions [6] and a $Q^2$-cut of 0.3 GeV$^2$. The result is $a_{\nu n} = 8.81$, $a_{\nu p} = 4.51$, $a_{\bar{\nu} n} = 2.50$, $a_{\bar{\nu} p} = 3.99$, $b_{\nu n} = 2.20$, $b_{\nu p} = 1.97$, $b_{\bar{\nu} n} = 1.15$ and $b_{\bar{\nu} p} = 1.14$.

One can easily find that neutrino interactions can be neglected in the Earth, but not in the Sun. The effective thickness of protons and neutrons, $T_p$ and $T_n$, of the Sun is calculated by using the solar model of Bahcall et al. [7] with the result $T_p = 1.1 \times 10^{12}$ g/cm$^2$ and $T_n = 3.6 \times 10^{11}$ g/cm$^2$.

We have approximated the Sun with a piece of homogeneous material with the thicknesses of protons and neutrons given above. For each produced neutrino we have calculated the mean free path for interactions and if an interaction has taken place, it is chosen to be a neutral or a charged current. In case of a charged current, the neutrino is treated as absorbed and in case of a neutral current, the scattering is simulated with PYTHIA 5.6 and the procedure is continued with the new energy of the neutrino until the neutrino has reached the surface of the Sun. 

This differs from the approach of Ritz and Seckel [2], which is the common approach, where the energy loss is considered to be continuous and neutral currents are assumed to be much weaker than charged currents. Neither of these assumptions is very good. In general, a neutrino only participates in a few interactions ($\sim 0$–2) on the way out of the Sun. Hence the process is highly discrete. In Fig. 1, the neutrino spectrum at the surface of the Sun is shown for injection of 500 GeV muon neutrinos and anti-neutrinos in the core of the Sun. The difference between the ap-
In Fig. 1b, the neutrino spectrum weighted by the spectrum is significant and it gets important however, the difference in the high energy tail of the energy. The difference between the two methods can clearly be seen, even though it has been somewhat washed out when applying the methods to a neutrino spectrum in the core of the Sun. In Fig. 1b, the neutrino spectrum weighted by the energy and the range of the muon is proportional to the energy. The difference between the two methods can clearly be seen, even though it has been somewhat washed out when applying the methods to a neutrino spectrum in the core of the Sun. However, the difference in the high energy tail of the spectrum is significant and it gets important due to the $E_{\nu}^2$-enhancement. If one uses the Ritz and Seckel approach, the error in the total rate is significant, and of the order of 5—20% too low with the higher error at higher neutralino masses ($\sim 1500$ GeV).

### Table 1

Parameterization (according to Eq. (1)) of the muon fluxes for different annihilation channels. With these values the unit of the flux in Eq. (1) is m$^{-2}$ (annihilation)$^{-1}$. An angular cut of $\theta < 5^\circ$ has been applied.

#### Annihilation in the Sun

| Channel    | $p_1$       | $p_2$       | $p_3$       | $p_4$       | $p_5$       | $p_6$       | $p_7$       | $p_8$       |
|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $c\bar{c}$ | $2.39 \times 10^{-38}$ | 0.269       | 0.00321     | 0.0598      | 0.00937     | $-0.0113$   | 0.0119      | 0.0          |
| $b\bar{b}$ | $6.03 \times 10^{-38}$ | 0.301       | 0.00277     | 0.0687      | 0.0185      | $-0.00882$  | 0.0112      | 0.0          |
| $t\bar{t}$ | $3.27 \times 10^{-37}$ | 1.31        | 0.000355    | 0.196       | 0.000399    | $-1.18$     | 0.00484     | 4.50         |
| $\tau^+\tau^-$ | $2.10 \times 10^{-37}$ | 0.590       | 0.00123     | 0.104       | 0.0240      | $-0.222$    | 0.00108     | 0.0          |
| $W^+W^-$   | $2.78 \times 10^{-37}$ | 1.26        | 0.00110     | 0.229       | 0.000657    | $-0.780$    | 0.00343     | 3.63         |
| $Z^0Z^0$   | $4.14 \times 10^{-37}$ | 1.52        | 0.000948    | 0.291       | 0.000368    | $-1.14$     | 0.00351     | 3.76         |

#### Annihilation in the Earth

| Channel    | $p_1$       | $p_2$       | $p_3$       | $p_4$       | $p_5$       | $p_6$       | $p_7$       | $p_8$       |
|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $c\bar{c}$ | $6.44 \times 10^{-29}$ | 0.226       | 0.00283     | 0.0645      | 0.00213     | $-0.0199$   | 0.00152     | 0.0          |
| $b\bar{b}$ | $9.42 \times 10^{-29}$ | 0.187       | 0.00531     | 0.0787      | 0.00513     | 0.0384      | 0.00350     | 0.0          |
| $t\bar{t}$ | $2.48 \times 10^{-28}$ | 0.830       | 0.000865    | 0.114       | 0.00581     | $-0.667$    | 0.0         | 0.0          |
| $\tau^+\tau^-$ | $2.45 \times 10^{-28}$ | 0.152       | 0.00533     | 0.113       | 0.00629     | 0.194       | 0.00103     | 0.0          |
| $W^+W^-$   | $2.38 \times 10^{-28}$ | 0.188       | $-0.000672$ | 0.130       | 0.00832     | 0.164       | 0.00259     | 0.0          |
| $Z^0Z^0$   | $2.87 \times 10^{-28}$ | 1.33        | $-0.000171$ | 0.126       | 0.00875     | $-1.01$     | 0.00271     | 0.0          |

4. Simulation results

The muon flux at the surface of the Earth has been calculated for different annihilation channels and for different neutralino masses. The annihilation channels considered are $c\bar{c}$, $b\bar{b}$, $t\bar{t}$, $\tau^+\tau^-$, $W^+W^-$ and $Z^0Z^0$ for the reasons stated earlier. The simulation has been performed with neutralino masses of 50, 100, 150, 200, 250, 350, 500, 750, 1000 and 1500 GeV and a top quark mass of $m_t = 150$ GeV. For easy use, the calculated fluxes have been parameterized as

$$
\frac{d\Phi_\mu}{dz}(m_\tilde{\chi}, z) = \frac{p_1 m_\tilde{\chi}}{1 + \exp \left( \frac{z - p_2 \exp(-p_3 m_\tilde{\chi} - p_8)}{p_4} \right)} \times \left[ 1 - \exp \left( -p_5 \frac{m_\tilde{\chi}}{z p_8} \right) \right] \exp(-p_7 m_\tilde{\chi} z) \quad (1)
$$

where $m_\tilde{\chi}$ is the neutralino mass in GeV, $z = E_\mu/m_\tilde{\chi}$ and $p_1, \ldots, p_8$ are the parameters fitted to the simulation results. The values of the fitted parameters are given in Table 1. If one calculates the total flux above a certain threshold, these parameterizations are accurate to $\sim 15\%$ as long as the threshold is not too close to the neutralino mass ($E_\mu^{th} \lesssim 0.2m_\tilde{\chi}$). The parameterizations are poorest for the $c\bar{c}$-channel and the $b\bar{b}$-channel in the Sun at high neutralino masses ($\gtrsim 500$ GeV), but these channels are not expected to dominate the flux at these high masses. The accuracy of the $\tau^+\tau^-$, $W^+W^-$ and $Z^0Z^0$ parameterizations are usually of the order of 5% and never worse...
than 10% and these channels usually dominate the flux.

The event rate at a detector is given by
\[ \Gamma_{\text{events}} = \Gamma_A A_{\text{eff}} \sum_i B_i \Phi_i \]
where \( \Gamma_A \) is the annihilation rate, \( A_{\text{eff}} \) is the effective area of the detector in the direction of the Sun/Earth, \( B_i \) is the branching ratio for annihilation channel \( i \) and \( \Phi_i \) is the muon flux (over threshold for the detector) per unit area and annihilation. \( \Gamma_A \) and \( B_i \) depend on the supersymmetric parameters chosen and are considered in other papers (e.g., [4]).

5. Example

For a specific supersymmetric model and a specific detector, one can calculate the event rate. Consider a neutrino detector with an effective area of 2000 m\(^2\) (a typical size for AMANDA [8] in the first set-up) in the direction of the Sun. For a Minimal Supersymmetric Model with parameters \( \mu = 300 \text{ GeV}, M_2 = 600 \text{ GeV} \) and \( \tan \beta = 2.0 \), giving \( m_{\tilde{\chi}} \simeq 250 \text{ GeV} \), one gets the expected event rate shown in Fig. 2 where the annihilation rate and the branching ratios are given by [9]. Note that this specific example is not yet excluded by other experiments.

6. Conclusions

The treatment of neutrino propagation through the Sun has been improved (the approach of Ritz and Seckel [2] was shown to give an error of up to \( \sim 20\% \)) and the calculated muon fluxes are given in an easy-to-use parameterization. The large neutrino telescopes now being built should have good possibilities to search through new parts of the supersymmetric parameter space.

Acknowledgments

I am grateful to L. Bergström, P. Gondolo and G. Ingelman for valuable discussions and comments.

REFERENCES

1. J. Edsjö, TSL/ISV-93-0091 preprint, Uppsala University, ISSN 0284-2769.
2. S. Ritz and D. Seckel, Nucl. Phys. B304 (1988) 877.
3. M. Kamionkowski, Phys. Rev. D44 (1991) 3021.
4. M. Mori et al., Phys. Rev. D48 (1993) 5505.
5. T. Sjöstrand, PyTHIA 5.6 and JETSET 7.3. Physics and Manual, CERN-TH.6488/92, T. Sjöstrand, Comp. Phys. Com. 39 (1986) 347, T. Sjöstrand and M. Bengtsson, Comp. Phys. Com. 43 (1987) 367, H.-U. Bengtsson and T. Sjöstrand, Comp. Phys. Com. 46 (1987) 43.
6. M. Glück, E. Reya and A. Vogt, Z. Phys C53 (1992) 127.
7. J.N. Bahcall and R.K. Ulrich, Rev. Mod. Phys. 60 (1988) 297.
8. AMANDA: Design of a 1 Kilometer Deep High Energy Neutrino Telescope, Proceedings, 23rd International Cosmic Ray Conference, Calgary, Canada, 19-30 July 1993, Vol. 4, p. 561.
9. L. Bergström, private communication.
10. T.K. Gaisser and T. Stanev, Phys. Rev. D30 (1984) 985.