Fluxes of Atmospheric Leptons in Large Underground Detectors

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Abstract

Four large under-water/ice detectors (AMANDA, Antares, Baikal, NESTOR) are presently at different stages of planning and operation. To fulfill their main purpose as neutrino telescopes these detectors have to suppress a background of atmospheric muons by 4 to 6 orders of magnitude. This necessitates a detailed understanding of the atmospheric muon flux. The measured atmospheric muon flux can further be used to calibrate these detectors and to constrain primary interaction models. Extensive CORSIKA Monte Carlo generation of high energy muons and neutrinos for different primary interaction models (QGSJET, SIBYLL, VENUS, HDPM) was performed, and the results were compared to existing measurements. Several modifications to this program were made to ensure an accurate representation of the conditions of the experiments. Based on this, the systematic uncertainties of the Monte Carlo and the potential of this detector type for cosmic ray physics were investigated.

1 Introduction:

For the search for high-energy extraterrestrial neutrinos a typical detection volume of ~ 1 km^3 is needed (Gaisser, Halzen, & Stanev, 1995). Existing detectors look for Cherenkov photons in a naturally occurring transparent medium (Halzen, 1999). The signal consists of muons, stemming from interactions of cosmic neutrinos in the detector, and the main background consists of muons coming from the air showers, initialized by charged cosmic rays at the top of the atmosphere and developed down to the level of observation. The chemical composition and energy spectra of these cosmic rays are well known from balloon and satellite experiments (Wiebel-Sooth & Biermann, 1999) in the energy range below 100 TeV. In order to simulate the detector response to this muon source, protons or heavier nuclei are generated at the top of the atmosphere and propagated down to the Earth's surface. The resulting air showers contain muons and neutrinos, which are propagated through the water or ice to the detector. Using the best knowledge of the detector medium available, Cherenkov photons are created and propagated to optical receivers. This Monte Carlo signal is used for the same reconstruction procedures as the real data obtained from the detector, and compared against this data. For the experiments positioned 1500 m $-$ 2500 m deep underground, the background of downgoing muons is 4 orders of magnitude higher than the signal of upgoing muons due to atmospheric neutrinos, and 6 orders of magnitude bigger than the expected muon flux due to extraterrestrial neutrinos. Therefore a high rejection of downward going muons has to be achieved, and a realistic simulation of all possible event topologies in the detector has to be performed.

2 Monte Carlo Studies:

This work represents an attempt to determine the accuracy of the existing air shower programs. The systematic uncertainties in air shower description by the different interaction models have been studied in detail in (Knapp, Heck & Schatz, 1996). In this contribution a special emphasis on the produced high energy leptons, as pertains to the logic outlined in the introduction, is placed. We used CORSIKA (version 5.42), which implements the high energy interaction models QGSJET, SIBYLL, VENUS and HDPM (Heck, et al., 1998). The presented calculations were made for the location of the AMANDA detector at the South Pole.

In CORSIKA it is possible to use any primaries with their correct spectra. In order to fully utilize this ability we modified CORSIKA to accommodate primaries from H to Fe with their measured spectra taken from (Wiebel-Sooth & Biermann, 1999) in the parametrized ($\Phi_0 E^{-\gamma}$) form, valid in the energy range above

100 GeV. Another modification was the change of the zenith-angle distribution function of primaries from the default for a flat detector to $dN \propto d\Omega \cdot (\pi r^2 \cdot \cos\vartheta + l \cdot 2r \cdot \sin\vartheta)$ for a cylindrical one with radius r and length l, as all four detectors mentioned in the abstract are cylindrical. This modification saves computational time when compared to the spherical detector model, since e.g. the visible area averaged over zenith angle of a spherical detector of the diameter 400 m will be as much as 3 times that of the cylindrical detector of the length 400 m and the radius 60 m.

In order to save disk space and computing time the detailed Monte Carlo simulation of EM cascades (EGS) was not performed. Instead, the results of the Nishimura, Kamata and Greisen (NKG) analytical description of the electromagnetic shower, giving the age parameter s and number of particles N_e, were recorded. The average distribution of particles on the observation level can then be obtained from the NKG formula, as given in (Heck, et al., 1998):

$$\rho_e = \frac{N_e}{2\pi r_{mol}^2 s_m^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} (\frac{r}{r_{mol} s_m})^{s-2} (1 + \frac{r}{r_{mol} s_m})^{s-4.5} \tag{1}$$

where $s_m = 0.78 - 0.21s$, $r_{mol} = 9.6g \cdot cm^{-2}/\rho_{air}$ = Moliere radius, and can be used to correlate the muon signal with the EM component at the surface. This approach neglects the photoproduction of pions and may lead to some loss in secondaries.

As it is, CORSIKA has 8 built-in atmospheres: one is US standard atmosphere, and seven are for the location of the KASKADE experiment in Karlsruhe. Atmospheres, generated by the MSIS-E-90 (Mass Spectrometer and Incoherent Scatter Extended Model) program (available at: NSSDC) for the location of AMANDA, for March 31st, July 1st, October 1st and December 31st, are compared (Fig. 1). October 1st and March 31st represent the typical behavior over the year.

To determine the magnetic field, a National Geophysical Data Center (NGDC) program (Available at: NGDC) (employing the model IGRF95) was used. For the South Pole on 12/31/1998 a field of 55911nT with the declination of $-27°43.0'$ (from a zero meridian) and inclination of $-72°54.5'$ was obtained. These values were used in CORSIKA.

The total of $1.5 \cdot 10^8$ primaries for QGSJET, $4.1 \cdot 10^7$ for SIBYLL, $3.0 \cdot 10^7$ for VENUS and $1.2 \cdot 10^7$ for HDPM were generated. The speed of the calculation in million generated primaries per day was 1.8 for QGSJET, 1.1 for SIBYLL, 0.36 for VENUS and 1.7 for HDPM interaction models. The total computing time amounted to 30 CPU weeks on 300 MHz Pentium IIs (Linux). The cutoff energy, both for the primaries and secondaries, was taken as 1.2 TeV. The incident angle was restricted to 0-70 degrees from the vertical, because a version of CORSIKA that was used, had a flat Earth approximation in it, which did not allow for angles bigger than 70° to be considered. The GHEISHA low energy interaction model did not affect the results of the calculation, since it only handles particles with energies lower than 80 GeV.

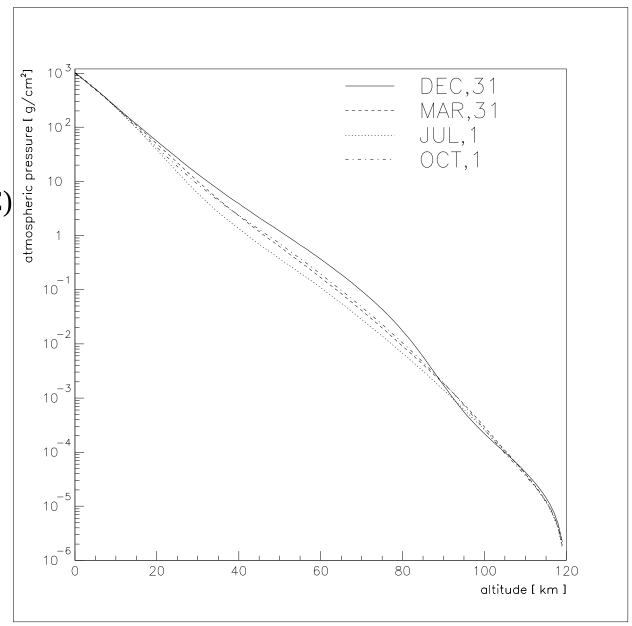

Figure 1: Comparison of 4 South Pole atmospheres.

3 Results:

In figure 2 the frequency of primaries producing muons above the energy of 1.2 TeV is plotted against the energy of the primary. The plot illustrates why the energy cut for the primaries and secondaries was taken to be the same. Due to the steep decrease of the energy spectrum already a small percentage of low energy primaries may cause significant deterioration in the flux of secondaries. A factor of 3 difference in the cuts implies that 2.3% of the muons are left out. Though this fraction may seem small, it renders the resulting muon data unusable, because an error in the muon index γ of up to 5% is detected, when compared to the muon index γ of the data with identical cuts.

The generated muon energy spectra were fitted with (Gaisser, 1990):

$$\frac{dN}{dE} \propto E^{-\gamma}\left(\frac{1}{1+\frac{1.1E_\mu \cos\vartheta}{115\text{ GeV}}} + \frac{0.054}{1+\frac{1.1E_\mu \cos\vartheta}{850\text{ GeV}}}\right), \qquad (2)$$

where the spectral index γ is a free parameter, expected to be close to that of the corresponding primary. Since this formula describes the energy and the number of muons at the point of production, two corrections to the muon data at the surface were made. First, the energy loss between production and the point where the muon hits the observation level was taken into account according to: $dE/dx = -(0.25 + 3.5 \cdot 10^{-4}E)$, x in mwe and E in GeV. Second, every muon was assigned weight $P^{-1} = \exp(\frac{l}{c\tau} \cdot \frac{M}{E}) > 1$, to account for the decayed particles. Here P is a probability of decay, τ, M and E are lifetime, mass and energy of the muon, c is speed of light and l is distance traveled by the muon.

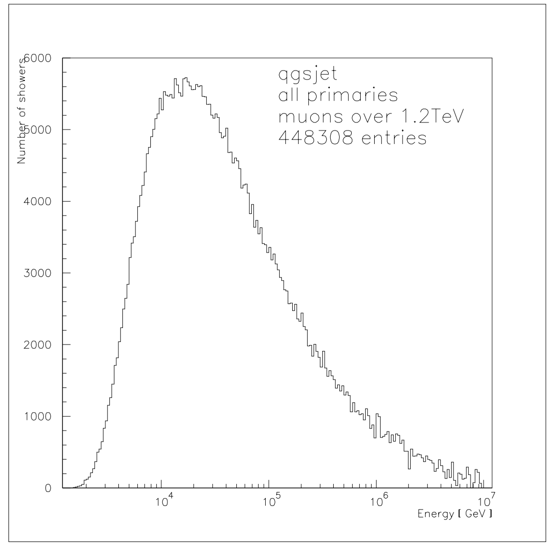

Figure 2: The muon response for all primaries and $E_\mu \geq 1.2$TeV.

Neutrino spectra were fitted with (Volkova, 1980):

$$\frac{dN}{dE} \propto E^{-\gamma}\left(\frac{1}{1+\frac{6E}{E_\pi(\vartheta)}} + \frac{0.213}{1+\frac{1.44E}{E_{K^\pm}(\vartheta)}}\right), \text{ for muon neutrinos,} \qquad (3)$$

where $E_\pi(\vartheta)$ was taken to be 202 GeV (for the average angle of $51°$), and $E_{K^\pm}(\vartheta) = 1500$ GeV, and

$$\frac{dN}{dE} \propto E^{-\gamma}\left(\frac{0.05}{1+\frac{1.5E}{E_{K^\pm}(\vartheta)}} + \frac{0.185}{1+\frac{1.5E}{E_{K_2^0}(\vartheta)}} + \frac{11.4E^{\zeta(\vartheta)}}{1+\frac{1.21E}{E_\pi(\vartheta)}}\right), \text{ for electron neutrinos,} \qquad (4)$$

where $E_\pi(\vartheta)$ and $E_{K^\pm}(\vartheta)$ are the same as before, $\zeta = a + b\lg E$, $E_{K_2^0}(\vartheta)$ =324 GeV, $a = -0.355$, and $b = -0.23$. The results are summarized in the table below.

Int. Model	QGSJET	SIBYLL	VENUS	HDPM
N_μ/N_{pri}, %	0.2943 ± 0.0004	$0.3516 \pm .0009$	0.3303 ± 0.0010	0.3237 ± 0.0016
$N_{\nu(e)}/N_{pri}$, %	0.00232 ± 0.00004	0.00245 ± 0.00008	0.00328 ± 0.00010	0.00235 ± 0.00014
$N_{\nu(\mu)}/N_{pri}$, %	0.0605 ± 0.0002	0.0615 ± 0.0004	0.0813 ± 0.0005	0.0604 ± 0.0007
γ_μ	2.733 ± 0.006	2.763 ± 0.011	2.736 ± 0.013	2.74 ± 0.02
$\gamma_{\nu(e)}$	2.936 ± 0.074	2.74 ± 0.08	2.80 ± 0.28	2.64 ± 0.70
$\gamma_{\nu(\mu)}$	2.698 ± 0.011	2.768 ± 0.023	2.739 ± 0.022	2.77 ± 0.04
μ multiplicity	1.769 ± 1.163	1.718 ± 0.963	1.788 ± 1.223	1.744 ± 1.073
e multiplicity	46730 ± 18740	26580 ± 16970	26060 ± 17110	52650 ± 19000
altitude, km	24.410 ± 8.944	23.990 ± 8.975	24.490 ± 8.966	23.780 ± 9.070
μ spread, m	22.64 ± 30.67	22.37 ± 28.83	29.66 ± 50.09	27.35 ± 36.64
γ_μ, H only	2.772 ± 0.008	2.811 ± 0.013	2.783 ± 0.017	2.757 ± 0.024
γ_μ, He only	2.649 ± 0.011	2.669 ± 0.021	2.668 ± 0.023	2.74 ± 0.04

In this table the following numbers are used to compare the primary interaction models: the percentage of muons, electron and muon neutrinos per primary, and the spectral indices of muon, electron neutrino and

muon neutrino spectra. The muon and electron multiplicities, the altitude of muon production and the muon spread (the distance of muons detected on the observational level from the shower core) show mean values $\pm$ RMS deviations. The last two entries show the spectral index of the muon energy distribution for showers, initiated by proton or helium only.
The spectral indices of secondaries are to be compared to the following primary indices: $\gamma_H = 2.758 \pm 0.003$ (assumed value is 2.76), $\gamma_{He} = 2.632 \pm 0.003$ (assumed value is 2.63), and $\gamma_{pri} = 2.6851 \pm 0.0017$ - for all primaries considered together (from H to Fe).
Figure 3 shows the comparison between the normalized (to the number of showers in the first bin) graphs of multiplicities of muons for the different models. It illustrates that not only the total number of muons, but also the multiplicity distributions are model dependent.

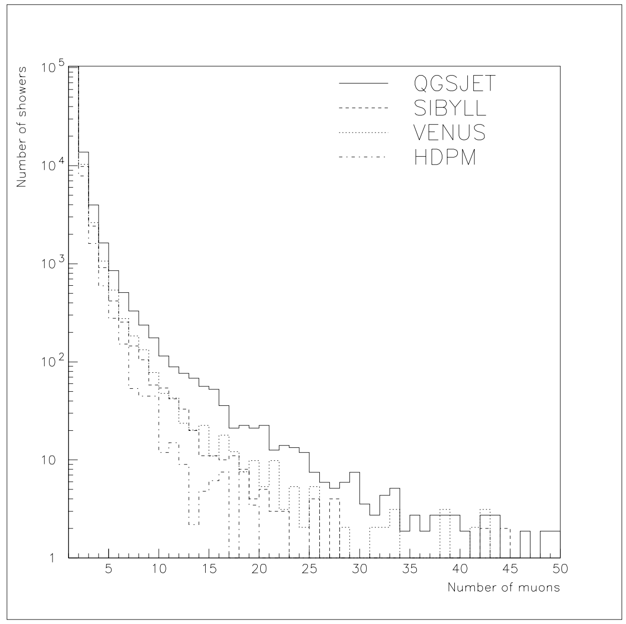

Figure 3: Multipicity of muons.

4 Conclusions:

SIBYLL gives a significantly larger γ_μ than the other models (also true if the primaries are only H). If the primaries are restricted to He, all 4 models give slightly bigger indices than $\gamma_{He} = 2.63$, with the highest deviation for HDPM. QGSJET is almost within one sigma from this value. VENUS gives much broader spread of muons on the observation level, with twice the RMS of the others. The fitted indices of the secondaries have been compared with the measured spectra in underground experiments. Muon spectral index values of 2.78 ± 0.07 (Frejus), 2.78 ± 0.05 (LVD), 2.76 ± 0.05 (MACRO) have been obtained in these experiments. The uncertainties due to the muon energy loss in underground experiments are of the same order as the uncertainty between the interaction models. All models agree within this error with the measurements. Further improvements must be made to the muon energy loss description in the water/ice routines to reduce systematic uncertainties in the experimental values in order to decide which model fits this data best. The muon neutrino index was measured to be $2.66 \pm 0.05(stat) \pm 0.03(syst)$ (Frejus Coll., 1995). The only models that agree with this value are QGSJET and VENUS. The electron neutrino index γ agrees with the theoretical prediction of (Volkova, 1980) for SIBYLL, VENUS and HDPM models, while QGSJET gives a significantly bigger value.

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