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An investigation of seasonal variations in the atmospheric neutrino rate with the AMANDA-II neutrino telescope

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Besides representing a source of background for the searches of astrophysical objects, atmospheric neutrinos are the most direct calibration source for neutrino telescopes. The characterization of this “test beam” has been, in the past, mostly based on the reconstruction of the energy spectrum and on flux measurements. In this work we investigate the amplitude and phase of possible seasonal variations in the event rate for the sample of 3329 neutrino candidates, detected with the AMANDA-II neutrino telescope in the years 2000-2003 (cfr. the AMANDA-II point source search, this conference). A mechanism that could produce such seasonal variations is the modulation of the target density for interactions of cosmic rays in the atmosphere. Its effect on the atmospheric muon rate is known and measurements have been performed using several underground detectors including AMANDA-II. Its effect on the rate of atmospheric neutrinos at energies above a few hundred GeV has not been studied before. In this paper we report about a calculation of the seasonal variations expected using a global temperature model for the atmosphere. The results are compared to the event rate of the AMANDA-II neutrino sample.

1. Introduction

One of the major goals of the large-scale neutrino detectors, AMANDA and IceCube, is to identify cosmic sources of high-energy neutrinos (>100GeV). This search is performed by reconstructing the direction of neutrino-induced muons using the pattern of their Cherenkov light emission. Muons and neutrinos produced in the interaction of cosmic rays with the atmosphere form the dominant background for this analysis. Both types of particle are generated in the decay of charged mesons ($\pi^{\pm}$, $K^{\pm}$), which originate in the inelastic scattering of cosmic ray primaries with nuclei of the atmosphere. The muons lose energy by electromagnetic interactions in the ice and rock surrounding the detectors and can therefore not penetrate more than a few kilometers into dense materials. Consequently, this background can be readily removed by restricting the observation to particles traveling in upward direction in the ice. Atmospheric neutrinos however reach the detectors from all directions and can not be distinguished from extra-terrestrial neutrinos. Therefore they remain as a residual background in the data sample, and it is essential to study the properties of this background well to quantify correctly possible deficits and excesses that would be interpreted as neutrino sources.

The search for variations of the atmospheric neutrino rate in time is an example for such a study. We report here on an investigation dedicated to seasonal variations in the atmospheric neutrino rate in the AMANDA-II detector. Annual temperature fluctuations of the atmosphere could be responsible for such variations. We perform a calculation of the expected magnitude of oscillation in the AMANDA-II event rate caused by this effect. The results of these calculations are compared with atmospheric neutrino data from the AMANDA-II neutrino telescope, recorded in 2000-2003 (the data sample used for the point source analysis [1]).

2. Seasonal variations

It has been shown that temperature variations in the atmosphere lead to changes in the intensity of the cosmic ray induced muon flux [3]. This effect has been measured by several experiments, among them MACRO [2] and AMANDA-B10 [4]. Since neutrinos and muons are produced in the same decays one might expect a corresponding variation in the neutrino rate. However, for several reasons the magnitude of these rate oscillations for neutrinos can not be derived directly from the muon rate changes using AMANDA-II or similar detectors:

1. The energy threshold for muons is higher than for neutrinos ($E^{\mu}_{thres} \approx 400$ GeV, $E^{\nu}_{thres} \approx 50$ GeV) due to the deep underground location of the detector.
2. For kinematic reasons the atmospheric neutrinos result predominantly from kaon decay, the muons from pion decay [6].
3. The muons originate from the local atmosphere above the detector while neutrinos are observed from interactions anywhere in the earth's atmosphere.

For these reasons, the analytic high-energy approximations, as used in [2] to calculate the variation in the muon flux, is not valid for neutrinos. At high energy (E $\gg$ 115 GeV for $\pi^{\pm}$, E $\gg$ 850 GeV for $K^{\pm}$) meson interaction dominates over meson decay making the muon and neutrino flux more sensitive to temperature variations [5]. However, for the low energy threshold of AMANDA-II, free decay plays an important role. The meson flux reaches its maximum at an altitude of $X \approx 10$ - 20 km, so temperature variations at high altitudes have to be taken into consideration. The lack of global high altitude temperature data makes it necessary to use an atmospheric temperature model instead of measurements. There is a variety of such models available ranging from ground to an altitude of several hundred kilometers (an overview can be found at [9]). A numerical calculation is performed here based on the NRLMSISE-00 atmospheric model by [8].

The neutrino flux at a certain atmospheric depth X at energy E produced by $\pi^{\pm}$-decay can be expressed using a derivation given by Gaisser [5]:

$$\Phi_{\nu}(E,X,\theta) = N_{\pi}\,\frac{\epsilon_{\pi}}{(1-r_{\pi})\cos\theta}\int_{E(1-r_{\pi})^{-1}}^{\infty}\frac{E'^{-2.7}e^{-X/\Lambda_{\pi}}}{XE'}\int_{0}^{X}\left(\frac{X'}{X}\right)^{\frac{\epsilon_{\pi}}{E'\cos\theta}}\exp\left(\frac{X'}{\Lambda_{\pi}}-\frac{X'}{\Lambda_{n}}\right)dX'\,\frac{dE'}{E'}$$

where Λ_{π}, Λ_{n} are pion and nucleon attenuation lengths and ϵ_{π} is the critical energy distinguishing between decay and interaction dominated regimes. θ is the angle between cosmic ray primary and atmosphere normal, $r_{\pi} = 1 - m_{\mu}^{2}/m_{\pi}^{2}$ and N_{π} is a normalization constant. To compute the neutrino flux produced by kaon decay the constants Λ_{π}, ϵ_{π}, r_{π} and N_{π} have to be replaced by their kaon counterparts. The temperature dependence in this representation is hidden in the critical energy $\epsilon_{\pi} = \epsilon_{\pi}(T(X))$ [2, 5]. The temperature as a function of atmospheric depth $T(X)$ is provided by the NRLMSISE-00 model.

By integrating the equation above, one obtains the total flux above a threshold energy E_{thres}. The expected event rate in AMANDA-II is obtained by weighting the energy integral with the effective area of the experiment:

$$n_{\nu}(\theta) = \int_{E_{thres}}^{\infty} A_{eff}(E,\theta)\int_{0}^{\infty}\Phi_{\nu}(E,X,\theta)dEdX$$

The integration of these equations can only be performed numerically; the technique used here is Monte Carlo integration. The neutrino flux is calculated for a grid of θ ($\theta < 60^{\circ}$) and d (day of the year) values. In figure 1 we show some results of this calculation for different threshold energies as well as with an additional weight, accounting for the AMANDA-II effective area. The maximum relative neutrino flux deviation from the mean is shown as a function of geographical latitude in the left plot; the time development for a selected geographical

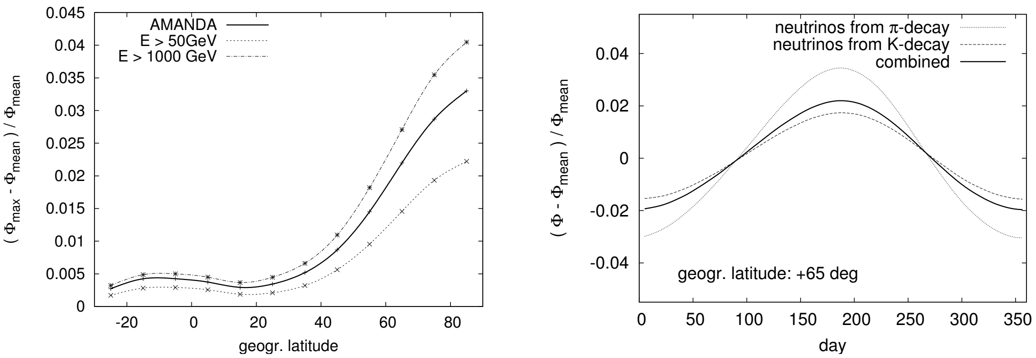

Figure 1. Left plot: Calculated geographical latitude dependence of the amplitude of the seasonal atmospheric neutrino flux variations relative to its annual average. The dotted line corresponds to the flux integrated above 50 GeV, the dashed line to the flux above 1 TeV. The solid line is integrated above 50 GeV but the flux is weighted with a parametrization of the AMANDA-II effective area. Right plot: Calculated time development of the flux variations at a latitude of 65°N (E > 50 GeV, AMANDA-II effective area). The dotted line shows the variation of the π-decay component alone, the dashed line the K-decay component. The solid line displays the combination of both components.

latitude is illustrated on the right. Notice that for neutrinos detected in AMANDA-II there are simple relations between geographical latitude l, θ and the declination δ, which are $\theta = 1/2(90^\circ - l)$ and $\delta = 90^\circ - \theta$.

One can see that the expected variability of neutrino fluxes in AMANDA-II ranges between 3.5% for particles from high latitudes and less than 0.5% from low latitudes, where seasonal temperature changes become very small. The maximum flux for high latitudes is expected around day 190, the minimum flux around day 360. Even for the highest latitudes the variation is considerably smaller than the $\approx 9\%$ seasonal flux variation measured for muons in AMANDA-B10 [4].

3. Comparison to experimental data

The AMANDA-II 2000-2003 point source sample provides a good set of events for investigating seasonal variations in the neutrino rate. While a small fraction of the events in this sample are expected to come from mis-reconstructed muons, the majority forms the largest sample of high energy atmospheric neutrinos available in AMANDA-II. For this analysis the data is divided into 3 angular regions.

declination δ	geogr. latitude l	# events	description
$0^\circ < \delta \leq 30^\circ$	$-90^\circ < l \leq -30^\circ$	1227	excluded from analysis, bin contaminated with misreconstructed down-going muons
$30^\circ < \theta \leq 60^\circ$	$-30^\circ < l \leq +30^\circ$	1492	equatorial region
$60^\circ < \theta \leq 90^\circ$	$+30^\circ < l \leq +90^\circ$	610	northern hemisphere, high latitudes

The small number of angular bins is due to the limited statistics of 3329 events in the AMANDA-II atmospheric neutrino sample. Figure 2 (right) shows the annual expected relative flux oscillation, from the calculation described above, for the equatorial and high latitudes region. In the high latitude region, $\Delta\Phi_{max}/\Phi$ is approximately 1.2% while for the equatorial region it is below 0.5%. So, in both cases the seasonal variations should be well hidden within the statistical error of the sample. Therefore we can only test if we find data rate variations in AMANDA-II which are incompatible with such a small modulation.

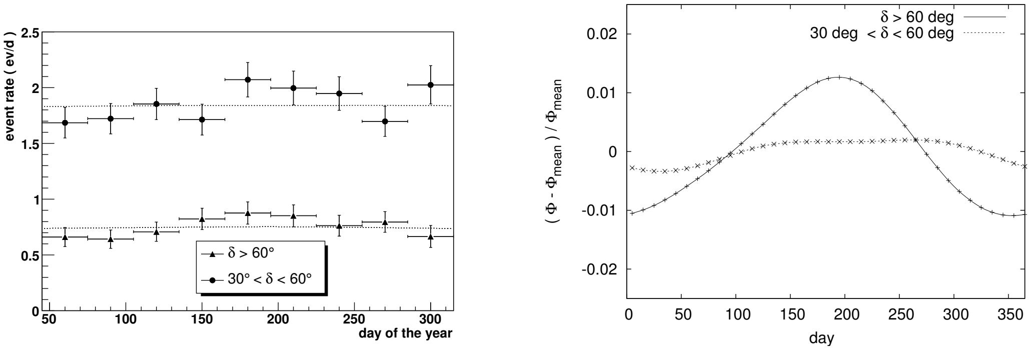

Figure 2. Left plot: Event rates in the AMANDA-II neutrino telescope vs. time coming from geographical latitudes above $30°N$ ($\delta > 60°$) and between $30°S$ and $30°N$ ($30° < \delta \leq 60°$). The dotted lines correspond to fits with a constant event rate plus the calculated relative modulation. Right plot: Relative seasonal variations of the atmospheric neutrino flux expected for these latitude bins from the numerical calculations described above.

Figure 2 (left) shows the AMANDA-II event rates in 30 day bins for the two latitude regions (with the years 2000-2003 superimposed in the same bin). These event rates have been corrected for dead-time and down-time of the detector. The distribution is fitted with the calculated intensity variations on top of a constant function. The χ^2 for the high latitude bin is $\chi^2/n_{free} = 6.6/8$, the value for the equatorial bin is $\chi^2/n_{free} = 8.8/8$. The distributions are compatible with the flux variations calculated.

4. Conclusions

For the first time the expected amplitude of seasonal variations in the atmospheric neutrino rates due to temperature fluctuations was calculated for a high energy neutrino detector. The calculations result in a variation ranging between 0.5% and 3% depending on the geographical latitude, which is too small to be resolved within the limited statistics of high energy atmospheric neutrinos from the AMANDA-II detector. IceCube and other km^2-detectors will provide samples with hundreds of thousands of atmospheric neutrinos [7], allowing precision measurements of fluxes. Atmospheric neutrino rate modulations on the 1% level will be measurable with these detectors.

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