DIFFUSE NEUTRINO FLUX

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ABSTRACT

The search for a diffuse neutrino flux component from astrophysical sources complements searches for point sources. In 2010 and 2011 many new results have been published on this subject. Realistic models can now be tested with these new measurements from the leading neutrino telescope experiments. An overview over these recent results is given.

1. Introduction

Neutrinos are produced in a variety of sources throughout the universe. The most prominent natural neutrino point source is our Sun. By exploring the angular correlation between the neutrino arrival direction and the position of the Sun, the solar origin of these neutrinos could be undoubtedly proven. However apart from our Sun no other permanent neutrino sources could be identified so far. An alternative is the search for a diffuse neutrino flux. Individual sources cannot be distinguished but the spectral shape of their integral contribution might be used to distinguish them from possible background. Such a diffuse neutrino flux might exist at very different energies.

A large contribution is predicted from neutrinos which decoupled from thermal equilibrium at a temperature of the universe of about 1 MeV. Due to the expansion of the universe these neutrinos (equipartitioned over all flavours) are expected to have today a black body radiation spectrum with a mean energy in the meV region. From measurements of neutrino oscillations it is known that the two heavier neutrinos have masses of $m_2 > 9\,\text{meV}/c^2$ and $m_3 > 50\,\text{meV}/c^2$. Therefore they must be non-relativistic today. So far no experimental technique is known to detect them.

Another diffuse neutrino flux must exist when summing the neutrino yield of all stellar fusion processes in the history of the universe. These neutrinos are expected to have spectra similar to solar neutrinos with energies mainly in the region of 0.1 MeV to 10 MeV. At slightly higher energies (up to 50 MeV) one should find a diffuse flux from neutrinos which had been produced during neutron star formation at core collapse Supernovae explosions throughout the history of the universe. A search for such a neutrino flux has been done in the SuperKamiokande experiment. No signal is observed and a flux limit could be set. This is discussed in more detail elsewhere in these proceedings.

In the following we concentrate on the diffuse flux at energies $E_\nu > 1\,\text{TeV}$. Only the most violent processes in the universe such as Active Galactic Nuclei (AGNs)
or Gamma Ray Bursts (GRBs) can contribute in this energy range. Its observation requires significantly larger detectors compared to those found in underground sites. In the following, results from large scale Neutrino Telescopes are presented which use natural transparent media such as deep sea water or Antarctic ice. A detailed introduction into the concept and physics of these devices is found elsewhere in these proceedings [3]. Here results from the Baikal [4], AMANDA [5], ANTARES [6] and IceCube [7] Neutrino Telescopes will be discussed.

2. The cascade and the muon channel

Neutrino interactions in the vicinity of the detector lead to two distinct signatures which are exploited in independent analyses. The charged current interaction of muon neutrinos

\[ \nu_\mu (\bar{\nu}_\mu) + N \rightarrow \mu^\mp + X \] (1)

and the charged current interaction of tau neutrinos with a subsequent muonic decay

\[ \nu_\tau (\bar{\nu}_\tau) + N \rightarrow \tau^\mp + X \] (2)

\[ \tau^\mp \rightarrow \mu^\mp + \bar{\nu}_\mu (\nu_\mu) + \nu_\tau (\bar{\nu}_\tau) \] (3)

result both in a long muon track. At TeV and even more at PeV energies these muons have a range of several km in water or ice, largely exceeding the size of the detectors. The neutrino interaction vertex and the accompanying hadronic shower are outside the fiducial volume most of the time. The track signature yields a good angular resolution. This is in principle not needed for a search of a diffuse flux but it ensures a clean separation of an upward going neutrino signal from the background of downward going atmospheric muons. The muon energy at the detector is deduced from the energy loss dE/dx which is related to the “brightness” of the track in the detector. As the energy loss is mostly stochastic at TeV/PeV energies, the muon energy can only be estimated with a precision of about a factor two. The calculation of the related neutrino energy depends on the assumed neutrino flux because the muon track has to be extrapolated upstream the detector to the neutrino vertex.

All other neutrino interactions as neutral current reactions

\[ \nu_x (\bar{\nu}_x) + N \rightarrow \nu_x (\bar{\nu}_x) + X \] (4)

electron neutrino charged current interactions

\[ \nu_e (\bar{\nu}_e) + N \rightarrow e^\mp + X \] (5)

and charged current interactions of tau neutrinos with a subsequent non-muonic decay

\[ \nu_\tau (\bar{\nu}_\tau) + N \rightarrow \tau^\mp + X \] (6)

\[ \tau^\mp \rightarrow \nu_\tau (\bar{\nu}_\tau) + X \] (7)
lead to a so-called cascade signature with the exception of tau neutrino charged current interactions at energies above 10 PeV which would yield two distinct cascades, one at the neutrino interaction vertex and a second one at the tau decay point. This special case is not considered in the following.

As a result of these neutrino interactions one obtains a hadronic and, depending on the channel, also an electromagnetic shower. They are very narrow and have a longitudinal extension of at most a few tens of meters. Due to the large spacing of adjacent detector elements in the coarsely equipped neutrino telescopes it is impossible to distinguish electromagnetic from hadronic showers. The observable signature in the detector is in all cases an isolated “cascade”. Due to its small extension the angular resolution is much worse here than for the track signature. This compromises the up/down separation. The main background for the cascade search comes from bright electromagnetic showers (e.g. due to bremsstrahlung) which accompany downward going atmospheric muons. The energy resolution is instead much better than for the track channel. All particles but the escaping neutrinos are seen in the detector and the brightness of the events correlates directly to the cascade energy which in turn is closely related to the neutrino energy. When using containment conditions for the neutrino vertex an energy resolution of 20% is feasible in future studies in this channel.

Whereas the effective volume for the cascade channel is close to the equipped volume of the detector, it is significantly larger for the muon channel due to the very long muon range. This results in a better sensitivity of the track channel for searches. The full potential of the cascade channel is reached at PeV energies where the background from electromagnetic activities which accompany downward going muon tracks is less dominant.

3. Atmospheric Neutrinos

The major background for observing a TeV-scale diffuse neutrino flux consists in atmospheric neutrinos and downward going atmospheric muons. Atmospheric neutrinos are produced over a large energy range in interactions of primary Cosmic Ray particles (mainly protons) with nuclei in the Earth atmosphere. The resulting hadronic showers contain also short-lived particles like pions and kaons. The main sources of conventional atmospheric neutrinos are their decays

\[
\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \quad (8)
\]

\[
K^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \quad (9)
\]

\[
K^\pm \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \pi^0. \quad (10)
\]

The subsequent decay of the muon contributes only marginally to the multi-GeV neutrino flux as most of these muons reach the ground and they are stopped before decaying. The primary Cosmic Rays have a non-thermal \(E^{-\gamma}\) spectrum with \(\gamma \approx 2.7\).
As pions and kaons propagate a certain distance through the atmosphere and lose thereby energy before decaying, the resulting neutrino spectrum is softer with $\gamma \approx 3.7$.

The most recent published measurements of the high energy part of the atmospheric neutrino spectrum comes from the IceCube collaboration [5, 6]. One year of data (2008-2009) has been analysed with almost half of the final detector lines installed (40 out of 86). As much as 18,000 upward going $\nu_\mu$ candidate events have been selected for this analysis. So far only the track signature has been exploited to measure the atmospheric neutrino flux above 100 GeV. This has several reasons. First $\nu_\mu$ are more copiously produced than other flavours (see Equation 8-10) and neutral current interactions have a lower cross section than charged current reactions. Further the effective volume is larger for the muon track signal than for the cascade channel and finally the isolation of a clean upward going event sample is more difficult in the cascade channel, as discussed above.

Two methods have been used to extract the neutrino spectrum from the data, forward folding [5] and regularized unfolding [6]. Both methods give comparable results and they are also consistent with different conventional atmospheric neutrino flux calculations [10, 11]. A distinction between these different flux predictions is not possible within the precision of the measurement. The highest energetic events can be attributed to neutrinos with energies of more than 100 TeV, which are thereby the highest energetic neutrino interactions ever detected.

For neutrino energies above 10 TeV the decay of mesons which contain heavy quarks (c,b) starts to contribute to the atmospheric neutrino flux. As these mesons have typical decay lengths of only few mm, they do not lose energy before they decay and the resulting so-called prompt atmospheric neutrino spectrum follows closely the original Cosmic Ray spectrum, i.e. $\gamma \approx 2.7$. This should be seen as a hardening of the measured spectrum and has been searched for in one of the mentioned IceCube analyses [5]. The predictions for this prompt neutrino flux vary by up to a factor ten [12, 13, 14, 15, 16]. The largest contribution is obtained in the frame of the Recombination Quark Parton Model [14, 15, 16] (RQPM), a non-perturbative QCD approach. As no hardening of the neutrino spectrum is observed, the RQPM model from [14] can be excluded on a level of $3\sigma$ in [5]. Further the model from [13] contains free parameters. When choosing these parameters to maximize the prompt neutrino flux, this model can be excluded with $2\sigma$. The model from [12], which predicts the lowest prompt flux, can instead not be constrained by the current data.

4. Search for a diffuse neutrino flux from astrophysical sources

An upper bound for a diffuse neutrino flux from astrophysical sources has been derived by Waxman and Bahcall (W&B) [17]. Here it is assumed that the extragalactic Cosmic Ray spectrum for $E > 10^{18}$ eV is produced in sources where protons are
magnetically confined to undergo efficiently the photoproduction reaction

\[ p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+. \]  

(11)

The pions decay according to Equation 8 and produce neutrinos, whereas the neutrons escape from the acceleration site, decay and produce the observed high energetic Cosmic Ray spectrum. Therefore the predicted neutrino flux is closely related to the observed Cosmic Ray flux above \( E > 10^{18} \text{ eV} \) and should be proportional to \( E^{-2} \) over several orders of magnitude. The resulting upper bound (corrected for neutrino oscillations during propagation from the source to Earth) is shown on Figure 1. Other models try to circumvent the constraints of \( \frac{\mathbb{L}}{\mathbb{G}} \) and predict higher neutrino fluxes (see below). By now the sensitivity of the experiments is high enough to test some of these models.

4.1. The cascade signature

A search for cascade signatures from a diffuse neutrino flux has been performed by Baikal \(^1\), AMANDA \(^{18,19}\) and IceCube \(^{20}\). The details of these analyses vary. But one common feature is the major discriminating power of the event brightness, expressed in terms of hit counts or amplitude, which is used to distinguish the signal from background. For all these analyses the main background comes from electromagnetic showers, associated to downward going muons. None of the analyses finds an excess of events over the background expectation. This allows to derive limits for an \( E^{-2} \) signal flux. Table 1 compares the diffuse flux limits from these analyses.

| Experiment | Data taking | Energy range | \( E^2 \Phi \) |
|------------|-------------|--------------|---------------|
| Baikal \(^1\) | 1998 - 2002 | 20 TeV - 20 PeV | \( 2.9 \cdot 10^{-7} \) |
| AMANDA \(^{18}\) | 2000 - 2004 | 40 TeV - 9 PeV | \( 5.0 \cdot 10^{-7} \) |
| AMANDA \(^{19}\) | 2000 - 2002 | 200 TeV - 1000 PeV | \( 2.4 \cdot 10^{-7} \) |
| IceCube \(^{20}\) | 2007 - 2008 | 24 TeV - 6.6 PeV | \( 3.6 \cdot 10^{-7} \) |

Table 1: Comparison of the 90% c.l. diffuse flux limits for different experiments in the cascade channel. The rightmost column indicates the single-flavour limit which is derived from the all-flavour limit by applying a factor 1/3. The fluxes are given in (GeV cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)).

The second column shows the corresponding data taking period, the third and fourth columns the central energy range in which 90% of the signal events would be found. AMANDA has performed a special analysis searching for downward going ultra high energetic (UHE) events \(^{19}\). This yields the best current limit for energies above 200 TeV. As explained in section 2 all flavours contribute to the cascade channel. As neutral current reactions are flavour-blind, there is an exact equipartition between all flavours in this channel, whereas for charged current reactions the main (but not exclusive) contribution comes from \( \nu_e \). Therefore limits in column 5 are given as “all
flavour” limits, assuming that the flux at the detector is composed from all three neutrino flavours and both neutrino helicities in equal parts. The combination of Baikal \(^4\) and the AMANDA UHE \(^{19}\) results give the best limits over the whole energy range. To make these results compatible to the limits derived in the \(\nu_\mu\) track channel, they are converted to single flavour limits by simply dividing by a factor 3. The corresponding single flavour limits are given in the last column of Table \(^{11}\).

4.2. The muon track signature

AMANDA \(^{5}\), ANTARES \(^{21}\) and IceCube \(^8\) have performed searches for a diffuse flux in the muon channel. Track reconstruction is used to select a clean sample of upward going neutrino candidates. The energy is estimated by evaluating the “brightness per track length” which correlates with the muon energy loss and therefore the muon energy in the detector. Different methods are applied in the three analyses. A particularly simple one is used in ANTARES. Here the energy is estimated from the average hit multiplicity on those optical modules which are used in the track fit. A cut in this variable is used to select the final event sample \(^{21}\). 9 events remain to be compared to expected 8.7 from conventional atmospheric neutrinos \(^{10}\) and 2 from the most optimistic prompt neutrino flux in the frame of the RQPM \(^{16}\). Unlike in the IceCube analysis, \(^8\) prompt models cannot be constrained but limits for astrophysical \(E^{-2}\) fluxes are derived.

| Experiment   | Data taking | Energy range | \(E^{-2}\Phi\) |
|--------------|-------------|--------------|---------------|
| AMANDA \(^5\) | 2000 - 2003 | 16 TeV, 2.5 PeV | 7.4 \(\cdot\) \(10^{-8}\) |
| ANTARES \(^{21}\) | 2007 - 2009 | 20 TeV, 2.5 PeV | 5.3 \(\cdot\) \(10^{-8}\) |
| IceCube \(^8\) | 2008 - 2009 | 35 TeV, 7 PeV | 8.9 \(\cdot\) \(10^{-9}\) |

Table 2: Comparison of the 90\% c.l. diffuse flux limits for different experiments in the \(\nu_\mu\) channel. The fluxes are given in (GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)).

Table 2 compares the diffuse flux limits from the three analyses. The data taking periods are indicated in the second column. It is noteworthy that the ANTARES \(^{21}\) and IceCube \(^8\) results have been published with a very short delay after data taking. The energy range indicates (as for Table \(^{11}\)) the central range in which 90\% of the signal events are expected. The limits in the last column are for \(\nu_\mu\); they are single flavour limits directly comparable to the limits in the last column of Table \(^{11}\). It can be seen that the limits obtained in the muon channel are significantly better than the cascade limits. The larger effective volume and a better discrimination against background from downward going muons are responsible for this effect.

Figure 4 shows a comparison of recent published limits for \(E^{-2}\) diffuse neutrino fluxes as of early 2011. The Frejus \(^{22}\), MACRO \(^{23}\), AMANDA-\(\nu_\mu\) \(^5\) and ANTARES \(^{21}\) limits have been obtained in the \(\nu_\mu\) channel. The Baikal \(^4\) and
Figure 1: A comparison of published 90% c.l. upper limits for $E^{-2}$ diffuse neutrino fluxes as of early 2011. For details, see text.

AMANDA-II UHE [19] limits are from measurements in the cascade channel. For reference, the W&B [17] and the MPR [24] upper bounds for transparent sources are also shown. They are divided by two, to take into account neutrino oscillations. The grey band represents the expected variation of the atmospheric flux: the minimum is the Bartol flux [10] from the vertical direction; the maximum the Bartol+RQPM flux [16] from the horizontal direction. The central line is averaged over all directions. The figure has been taken from [21].

The ANTARES limit constrains various models. The MPR model [24], shown on Figure 1, can be excluded with 90% c.l. Similarily the models [25,26] are excluded with the same confidence level.

The most stringent limit is currently provided by the preliminary analysis from IceCube [8] which is not included in Figure 1. It is the first analysis which is sensitive enough to probe the region below the W&B [17] upper bound. The models which are excluded by the ANTARES analysis on 90% c.l. are here excluded on a 5σ level, as well as some other flux predictions [27,28,29].

5. Conclusion

During the last year a wealth of new results have been published on the search for diffuse neutrino fluxes from astrophysical sources. These searches complement point source searches. So far no excess of events beyond the expected rate of atmospheric
neutrino events has been found. The sensitivity of the analyses is already high enough to constrain or exclude various models. For the first time fluxes below the W&B upper bound are tested. Fast publication has become a standard which illustrates a good understanding of the used detectors and media.

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