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Coincident TeV Neutrino and Gamma Ray Observations

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Abstract: The IceCube detector is already the world's largest neutrino detector and when completed in 2011, will be a cubic kilometer in volume. However, even under optimistic assumptions about neutrino emission, the potential neutrino signal in IceCube from AGN and GRBs may be small. The atmospheric neutrino background after cuts will result in 1-2 neutrinos/yr/km^3/deg^2 above 1 TeV. For a three year observation of an AGN in the northern sky one could expect ~5 background events. Lacking other information about AGN emission in the TeV nearly 15 neutrino signal events would have to be observed in order to claim an unambiguous detection. The HAWC gamma ray detector would be a unique complement for IceCube. It will monitor the entire northern sky everyday for transients with fluxes less than 1 Crab in the TeV energy range. HAWC would detect stronger outbursts, such as have been observed for Mrk 501 and Mrk 421, within 10 minutes. It will also be a monitor for TeV emission from GRBs. By knowing when to look for TeV emission, IceCube could observe a neutrino signal with just 1-2 events. This paper will focus on the capability of HAWC as an all-sky TeV monitor and, in particular, its utility for neutrino detectors such as IceCube.

Introduction

The origin of charged cosmic rays has been a pressing question since their discovery 95 years ago. In recent years, numerous astrophysical sources of TeV gamma rays have been discovered. Detection of neutrinos from one or more of these gamma-ray sources will help identify the site of production of the charged hadrons that make up the majority of the cosmic rays. Therefore there is a strong motivation for a multi-messenger study of gamma ray sources.

The IceCube detector is already the world's largest neutrino detector [1] and when completed in 2011, will be a cubic kilometer in volume. However, even under optimistic assumptions about neutrino emission, the potential neutrino signal in IceCube from AGN and GRBs may be small. The atmospheric neutrino background after cuts will result in 1-2 neutrinos/yr/km^3/deg^2 above 1 TeV. [2,3]

The proposed HAWC detector [4] will be a survey instrument capable of expanding the limited catalog of TeV gamma ray sources and of daily monitoring of this catalog for flares. HAWC will not only detect new sources, but will detect transient emission so that deeper searches for TeV gamma ray and neutrino emission may be undertaken by instruments such as Veritas and IceCube. The HAWC detector is based on an extension of the design pioneered with Milagro. It combines water Cherenkov technology with a larger area, optical isolation and an extreme altitude site to give a sensitivity ~15 times that of Milagro (see

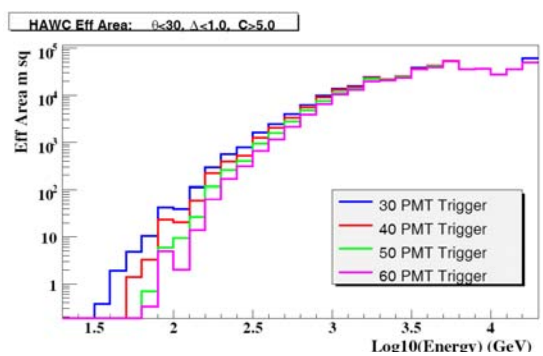

Figure 1: HAWC effective area for gamma-rays. This is for showers within 30^o of zenith, passing the gamma-hadron cut, which reconstruct within 1^o of the true angle. For a 30 pmt trigger HAWC will have nearly 70m^2 at 100 GeV and 10^{4}m^2 at 1 TeV.

Figure 1). HAWC, like Milagro, will observe the entire northern sky daily.

A TeV Sky Monitor

There are several known types of transient or variable sources relevant for a TeV gamma-ray observatory: active galactic nuclei (AGN), gamma-ray bursts (GRBs), micro-quasars and X-ray binaries. While there may be common features to the acceleration of particles, these sources are distinct and call for different observing strategies to detect them and study their temporal behavior. With several years of effort HESS has detected a number of AGN, but no GRBs. In addition, HESS has detected several micro-quasars and X-ray binaries. However because of the nature of IACTs it has been difficult for them to carry out an observation program capable of elucidating the nature of the acceleration process at work in these sources although they are making progress [5]. In all cases, an all-sky high-duty cycle observatory such as HAWC is capable of detecting and observing these sources over long time periods will be useful.

Why is an all-sky TeV monitor needed to carry out such a research program? AGN can flare to more than 10 times their quiescent luminosity. Recently, HESS has observed an AGN flare with a flux of 15 Crab [6]. An all-sky monitor can observe every AGN in the same hemisphere every day. Therefore, even phenomena that are rare for single AGN can be observed frequently when observing a large population of objects. GLAST should see many flaring objects, but will not have the high energy sensitivity to tell which of these objects are emitting TeV gamma rays.

GRBs occur roughly twice per day throughout the universe. Since they occur at random times and in random directions, only an all-sky, high duty cycle instrument can detect the initial emission from these objects. The chance that a GRB occurs in the field of view of an IACT is ~1/century. While MAGIC has slewed to satellite triggered GRBs, only a wide-field detector such as HAWC has a reasonable chance to see initial TeV emission from a GRB.

Other objects such as micro-quasars and X-ray binary systems can have long orbital periods (hours to years) and the high-energy emission is correlated with the orbital phase. Only by studying these objects over several orbital periods can we understand the mechanisms behind the acceleration process and the local conditions where particle acceleration occurs. Only an instrument like HAWC is capable of long term and continuous monitoring.

Since HAWC will always view every source (in its hemisphere) every day there will naturally be a large number of multi-wavelength and multi-messenger (with IceCube) observations. Such observations have proven essential for understanding the extreme sources that are bright at TeV energies.

What are the characteristics of HAWC that suit it to complete such an observational program? The instantaneous field-of-view of HAWC is approximately 2 sr. With the rotation of the Earth, HAWC will view over 2π sr of the sky every day. Based upon our experience with Milagro we known that we can achieve a duty cycle in excess of 90%, most likely near 95%. The sensitivity of HAWC is such that a source with a flux 5x that of the Crab Nebula can be detected (at 5σ) in a 10 minute period (and 15 Crab in 1minute). Given previous studies of AGN flaring structure this is more than sufficient to guarantee a large number of such detections.

The low-energy response and background rejection abilities of HAWC are such that a 100 second long GRB, with a fluence above 10^{-5} ergs cm^{-2} can be detected out to a redshift of 1 (see Figure 2). (Note this is the equivalent fluence that would have reached the Earth if there were no absorption by the EBL. The fluence at Earth required for a 5σ detection is ~10^{-7} ergs cm^{-2}.)

Synergy with IceCube

IceCube is a neutrino detector sensitive to TeV-PeV neutrinos from astrophysical sources. HAWC and IceCube will observe the same range of energies, and the proton cascade process produces comparable fluxes of photons and neutrinos at similar energies. Both HAWC and IceCube operate with nearly 100% duty cycle and both observe very large fields of view, making them very good instruments for observing transient phenomena. HAWC will be located so that it will have excellent coverage of both the Northern sky, which is visible to IceCube at TeV energies, and the mid-latitude region visible to IceCube in the PeV band.

Since the expected neutrino rate in IceCube from astrophysical sources is low, IceCube's sensitivity is limited by background. Contemporaneous detection of high energy gamma rays from astrophysical objects will greatly extend the sensitivity of IceCube by allowing searches targeted to known TeV sources during periods of active emission thus limiting background. Most importantly, by simultaneously measuring the neutrino and gamma-ray components of the source emission, we can gain a much better insight into the mechanisms responsible for particle acceleration and the environment within and around the acceleration sites. HAWC will perform such simultaneous measurements over essentially all sources in the field of view and energy range of IceCube.

IceCube's sensitivity at TeV energies is limited by the background of atmospheric neutrinos. To observe lower fluxes, one must restrict the search to neutrinos at higher energies, which reduces event rates and leads to the risk that neutrino emission might be missed entirely if the source spectrum does not extend to high energies. Only a handful of neutrino events are expected per source for fluxes comparable to those seen in TeV gamma ray sources. Knowing that only 1% of GLAST sources emit in the TeV band, for example, would increase IceCube's sensitivity to those sources by approximately a factor of 10, due to the reduction in statistical penalties.

The orphan flare from 1ES 1959 was particularly interesting because AMANDA (the predecessor to IceCube) observed one neutrino event from the direction of 1ES 1959 at approximately the same time (within a few hours).[7] This neutrino event was the second of three neutrinos observed from that direction over a period of 66 days (in total, 5 neutrinos from that direction were observed in the four year AMANDA-II data set). The third neutrino was also approximately coincident with a gamma ray flare, this time a conventional flare which was also observed in the X-ray band. No gamma ray observations were possible at the time of the first neutrino. The point here is that X-ray data cannot be used to reliably predict TeV emission. Indeed, the absence of X-rays may be an indicator of hadron acceleration. In order to understand the output of these objects in the TeV we must monitor them continuously in the TeV.

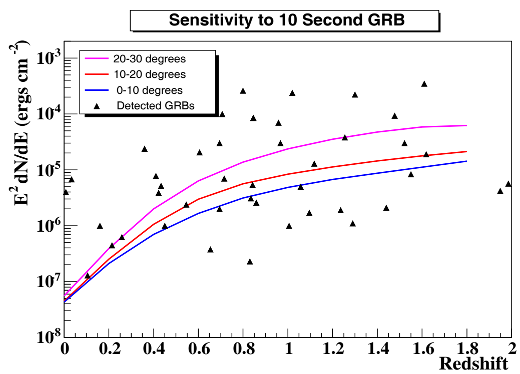

Figure 2: HAWC Sensitivity to a 10 second GRB. The lines are for GRBs at different zenith angles & the triangles are observed GRBs with known redshifts. It can be seen that HAWC has the potential to detect approximately half the GRBs in its field of view if their spectra extend above ~300 GeV

What can IceCube do in coincidence with HAWC?

After cuts IceCube will have an atmospheric background rate of ~1-2 neutrinos/yr/km^3/deg^2 above 1 TeV. Assuming a 1 deg^2 bin[1], for a three year observation of a specific point in space, IceCube will have approximately 5 background events in a bin surrounding a potential source. In order to claim an unambiguous detection of neutrinos from a source IceCube would need approximately 15 signal events on top of a background of 5. This would give a Poisson probability of $3x10^{-7}$ which is slightly larger than 5σ. (11 signal events on top of a background of 5 would be ~4σ).

If HAWC can provide a window of time where TeV emission is observed from a northern hemisphere source then the IceCube background is dramatically reduced, meaning that a much smaller signal will become significant. For example, since HAWC could detect a flare at the level of 2 Crab in 1 hour the IceCube background during one hour is $\sim 10^{-4}$. Thus 1 event would be approximately a 4σ detection and 2 events is greater than 5σ even after allowing for 20 potential trials. HAWC would see a 1 Crab flare in at 5σ a single transit. This would give IceCube a one day window. Two neutrino events in a day is greater than 4σ. This represents a nearly order of magnitude increase in sensitivity for IceCube. It should be noted that IceCube may be able to combine energy and position information to further reduce their background.

The IceCube collaboration is currently exploring a target of opportunity measurement with MAGIC, where MAGIC is to be targeted on one of a list of pre-selected AGN and micro-quasars when a neutrino is observed from the direction of that source [8]. While this has the potential to be fruitful and can be done with the existing detectors, it must be done in nearly real time and only during the ~10% of the time that an IACT can operate. Because HAWC operates continuously and views the northern sky every day it offers the opportunity to observe many flares which, since HAWC data will be archived, can be compared to the IceCube data at any time.

Conclusions

The HAWC gamma ray detector would be a unique complement for IceCube. It will monitor the entire northern sky everyday for transients with fluxes less than 1 Crab in the TeV energy range. HAWC would detect stronger outbursts, such as have been observed for Mrk 501 and Mrk 421, within 10 minutes. It will also be a monitor for TeV emission from GRBs. By knowing when to look for TeV emission, IceCube could observe a neutrino signal with just 1-2 events. HAWC will also be able to identify which of the many new sources GLAST will observe emit TeV gamma rays. This gives HAWC a unique capability of as an all-sky TeV monitor and, in particular, it will increase the sensitivity of neutrino detectors such as IceCube significantly.

Acknowledgements

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