NEUTRINO ASTRONOMY 2017

T.K. Gaisser

Department of Physics and Astronomy and Bartol Research Institute
University of Delaware, Newark, DE 19716, USA

This overview of neutrino astronomy emphasizes observation of astrophysical neutrinos by IceCube and interesting limits on Galactic neutrinos from IceCube and ANTARES.

1 Introduction

Neutrinos contribute in a unique way to multi-messenger astronomy. Being electrically neutral and weakly interacting, they reach Earth from the entire cosmos. They are associated with hadronic interactions in their sources, for example $p \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$, so they are likely to be tracers of cosmic-ray sources. Unlike cosmic rays, high-energy neutrinos travel without deviation by magnetic fields and therefore point back to their sources. Unlike high-energy gamma-rays, they do not cascade in the Cosmic Microwave Background (CMB) or in other Extra-galactic Background Light (EBL). The main problem is accumulating enough events to identify the neutrino sources. Even with the cubic kilometer size of IceCube, the accumulation of neutrinos likely to be of astrophysical origin is at the level of a few tens per year.

There are three high-energy neutrino detectors currently in operation, Baikal, ANTARES and IceCube, and there are active plans for expansion associated with all three. Recent results were presented at this conference by Antoine Kouchner\(^1\) for ANTARES and by Carlos Argüelles\(^2\) for IceCube. This paper will review the status of the search for both galactic and extra-galactic neutrinos. The basic situation is that IceCube has discovered astrophysical neutrinos at high energy above the steeply falling background of atmospheric neutrinos. The discovery came first in the High-Energy Starting Event (HESE) analysis\(^3\) in which events were required to start within an inner fiducial volume of IceCube. The excess is also seen at a consistent level in the upward moving sample of neutrino-induced muons\(^4\). The all-sky search for steady point sources in IceCube\(^5\), having identified no significant excess, sets the strongest limits on the intensity of neutrinos from a single point in the sky. The limits are improved at low energies in the Southern sky in the combined search by ANTARES and IceCube\(^6\). This is because ANTARES views the Southern sky through the Earth and therefore has a much lower background than IceCube, which sees the Southern sky through a large foreground of atmospheric muons.

2 Potential sources of high-energy neutrinos

It is natural to divide neutrino sources into two classes, Galactic and extra-galactic. Within each group, both diffuse neutrinos and neutrinos from point sources or compact regions of the sky are expected.
2.1 Neutrinos of Galactic origin

The one truly guaranteed population of high-energy extraterrestrial neutrinos arises from interactions of cosmic rays with gas in the disk of the Milky Way. The spectrum would be a power-law with the same spectral index as the parent cosmic-rays until the spectrum becomes steeper (around 100 TeV reflecting the steepening of the parent nucleon spectrum at the knee \( \sim 1 \text{ PeV} \)). The expected rate is obtained by calculating the neutrino emissivity per hydrogen atom given an assumption about the cosmic-ray spectrum in the interstellar medium (ISM) and then summing over the distribution of gas in the ISM. In the simplest case the cosmic-ray spectrum is assumed to be the same as observed at Earth everywhere in the disk (differential index \( \sim 2.7 \)) and the gas density is assumed to be independent of Galactic radius.

Because astrophysical neutrinos are produced mainly by decays of charged pions, the Galactic neutrino flux is closely related to the \( \pi^0 \) contribution to the corresponding component of the diffuse flux of gamma-rays. In a series of papers Gaggero et al. use the Fermi measurements of gamma-rays from different regions of the Galaxy to model cosmic-ray propagation in the inner Galaxy. They find that the parameter \( \delta \) that characterizes the energy dependence of the diffusion coefficient \( (D \propto E^\delta) \) decreases toward the center of the Galaxy compared to its value near Earth. This in turn implies that the parent spectrum of the pions is harder in the inner regions of the Galaxy so that the predicted neutrino spectrum is increasingly higher than in the conventional model as energy increases.

Current upper limits of both ANTARES and IceCube are close to the prediction of the KRA\(_c\) model. The limits from ANTARES are comparable to those of IceCube even though it is significantly smaller because the central region of the Galaxy is in its field of view. The possible contribution of a Galactic component to the HESE sample is a topic of interest. The IceCube analysis uses its gamma-ray templates to integrate the Galactic limits over the full sky in order to compare directly with fits to the diffuse astrophysical flux observed by IceCube. The conclusion is that Galactic contribution is < 14% of the astrophysical flux reported in. In other words, the Galactic plane is not yet resolved in neutrinos. The ANTARES analysis reaches a similar conclusion by comparing to HESE events consistent with being from the Galactic plane.

Neutrinos from sources in the galactic plane are also expected, in particular from supernova remnants accelerating particles into nearby molecular clouds. The IceCube analysis includes a stacking search based on catalogs of potential Galactic sources.

2.2 Neutrinos of extra-galactic origin

"Cosmogenic neutrinos" constitute a truly diffuse population of extragalactic neutrinos. This term refers to neutrinos from decay of charged pions produced by interactions of ultra-high energy cosmic rays (UHECR) with the CMB and EBL. Cosmogenic neutrinos are often referred to as "guaranteed" because both UHECR and CMB exist. However, if, as suggested by Auger data, the highest energy cosmic rays are mostly nuclei rather than protons, the neutrino flux may be so low that it is undetectable because the energy per nucleon would be below the threshold for photo-pion production on the CMB. IceCube limits on neutrinos with energy greater than 10 PeV already constrain predictions of cosmogenic neutrinos based on the assumption that the highest energy cosmic-rays are protons. The most recent limit from nine years of IceCube data gives a 90% confidence level differential upper limit on \( E_\nu^2 dN_\nu/dE_\nu \) that is below \( 2 \times 10^{-8} \text{ GeV cm}^{-2}\text{sr}^{-1}\text{s}^{-1} \) up to \( 10^9 \text{ GeV} \). Because neutrinos produced by interactions of cosmic-rays with energy per nucleon > \( 10^9 \text{ GeV} \) would produce neutrinos with \( E_\nu > 10^7 \text{ GeV} \), this result will constrain any model that connects the IceCube HESE flux shown in Fig. 1 to the flux of UHECR.
Neutrinos from cosmic-ray interactions in external galaxies

The same processes that accelerate cosmic rays in the Milky Way are at work in external galaxies. The conditions for interaction with gas to produce neutrinos may, however, be expected to vary from one galaxy to another. As a starting point, it is interesting to ask what signal would be expected from galaxies similar to the Milky Way. The isotropic flux from a distribution of sources with similar intrinsic luminosities $Q_{\nu}(E_{\nu})$ ($\nu$ per sec per GeV) is given by an integral over redshift $z$ as

$$\phi_{\nu}(E_{\nu}) = \frac{R_H}{4\pi} \int Q_{\nu}((1 + z)E_{\nu}) \rho(z) \frac{H_0}{H(z)} \, dz \sim \xi_z \rho_0 Q_{\nu}(E_{\nu}) R_H \frac{H_0}{4\pi}.$$  

(1)

Here the Hubble radius $R_H = \frac{c}{H_0} \approx 4000$ Mpc and $\frac{H(z)}{H_0} = \sqrt{\Omega_\Lambda + \Omega_m(1 + z)^3}$ with $\Omega_\Lambda = 1 - \Omega_m \approx 0.7$. The cosmological factor $\xi_z$, of order 1-3, depends on how the sources evolve in redshift. In his review of galactic neutrino sources, Markus Ahlers compares the flux calculated in Eq. 1 with the local flux from the Galactic plane but averaged over the full sky. By a dimensional argument, the latter is

$$\phi_{\text{loc}} \sim \frac{Q_{\nu}(E_{\nu})}{4\pi R_{MW}^2},$$  

(2)

where the radius of the Milky Way is $R_{MW} \approx 15$ kpc. The result is that the extra-galactic flux is a factor of two to three orders of magnitude less than the local flux for a density of $10^{-3}$ to $10^{-2}$ galaxies per Mpc$^3$ similar to the Milky Way.

In galaxies with more active star formation, the neutrino flux should be higher because of the larger rate of supernova explosions and the correspondingly higher flux of cosmic rays. In addition, the increased rate of turbulence may lead to a situation in which the cosmic rays typically interact with the gas before they escape from the galaxy, which is referred to as the “calorimetric limit.” The Fermi paper shows a positive correlation between the rate of star formation and the gamma-ray luminosity of external galaxies. In addition, the gamma-ray spectrum tends to harden with the rate of star formation as the spectrum of cosmic rays becomes closer to the source spectrum. A neutrino flux from the cumulative contribution of starburst
galaxies large enough to be observed in a kilometer scale neutrino detector was predicted by Loeb and Waxman a decade ago \cite{27} and discussed recently in the review paper of Waxman \cite{28}.

One question that arises is whether the same sources that produce the neutrinos observed by IceCube also explain the origin of UHECR. Figure 1 compares the spectral energy distribution (SED: $E^2dN/dE$) of three populations of particles, the diffuse Isotropic Gamma-Ray Background (IGRB) \cite{21}, the IceCube astrophysical neutrino flux \cite{16} and the high-energy end of the cosmic-ray spectrum \cite{22,23}. Waxman points out that the Waxman-Bahcall neutrino bound \cite{29,30}, normalized to the UHECR above $10^{19.2}$ eV and assuming an $E^{-2}$ spectrum for the extra-galactic component comes close to the level of the of the IceCube measurement, shown as the sum of three flavors of neutrinos and anti-neutrinos. The UHECR themselves are not, however, the particles that produce the neutrinos. In the starburst model the neutrinos are produced by cosmic-rays accelerated within each galaxy, perhaps in explosions of supernovae, when they interact with gas inside the galaxy. In this case (as in any scenario in which the neutrinos are produced by interactions of a spectrum of nucleons with ambient gas) the neutrino spectrum will extend to low energy. Then, unless the spectrum is quite hard, the model implies an overproduction of diffuse gamma rays compared to the Fermi measurement in Fig. 1\cite{31,32}. The problem is apparent from the figure (even before a calculation of the electromagnetic cascade in the CMB) given that the $\pi^0$ decay photon flux is similar at production to the neutrino flux. If the neutrino flux is as steep as shown in the figure, then it is not possible to account for the entire neutrino flux in the starburst model \cite{33}.

Another contribution to the neutrino flux can be expected from Type IIn supernovae in external galaxies \cite{34,35}. These are supernovae that explode into the dense wind of a progenitor star. The neutrinos are produced for a short time until the supernova shock breaks through the dense shell (up to a 30 year time scale). The paper \cite{35} notes one event in the HESE sample as being $1.35^\circ$ from SN2005bx at $z=0.03$. In his presentation at ISVHECRI 2016, Ptuskin noted that track #11 in the upward neutrino-induced muon sample \cite{4} is $0.3^\circ$ from SN2005jq at $z=0.23$. However, no systematic analysis of chance probability has yet been done. Moreover, a detailed calculation finds that only a fraction of the IceCube neutrino flux can be explained in this way \cite{36}.

**Neutrinos from active galaxies**

Active galaxies with relativistic jets driven by accretion onto the central supermassive black hole are potential sources of high-energy particles including neutrinos. In this case it is generally assumed that the neutrinos arise from photo-pion production by accelerated protons interacting with intense radiation fields in the inner regions of the system \cite{37}. Because of the high energy threshold for the production process, the neutrino spectrum and the corresponding spectrum of photons, do not extend down to low energy, as in the case of a spectrum of nucleons interacting with gas. In addition, much of the diffuse gamma-background is from unresolved blazars \cite{38}. There are blazars consistent with being from the direction of neutrinos in the HESE data sample \cite{39}, as well as at least one case of a coincidence with a flaring episode \cite{40}. However, a systematic search of the Fermi 2LAC catalog \cite{41,42} puts an upper limit of $\sim 20\%$ on the fraction of the HESE flux arising from sources in this catalog \cite{43}. The current status of neutrinos from active galaxies is reviewed by Murase \cite{44}. One possibility is that blazars with hard spectra contribute mainly at high energy and give only a fraction of the astrophysical flux at lower energy. (See also \cite{45}).

**Gamma-ray bursts**

Gamma-ray bursts (GRBs) are prominent candidates for the origin of UHECR \cite{46,47} as well as for high-energy neutrinos \cite{48}. Of the two main classes of gamma-ray bursts (GRBs), long bursts ($\geq 2$ s) associated with core collapse of massive stars are the most likely candidates for production of neutrinos \cite{49}. Acceleration may occur in shocks inside the relativistic jets driven by accretion onto a central remnant black hole. As with AGN jets, the production process is
photo-pion production off intense radiation fields, so the neutrino spectrum is characterized by an energy distribution that peaks in the PeV range\(^5\).

From the observational point of view, GRBs are ideal candidate sources, providing a time stamp as well as a direction from satellite observations. The latest IceCube study looks at more than 1000 identified GRBs and finds no significant correlations\(^5\).

### 3 Interpretation of present results

IceCube has identified a population of high-energy astrophysical neutrinos. Based on the distribution of events in the sky, no more than \(\sim 10\%\) of the observed signal is from neutrinos from the Milky Way. No sources have yet been identified, either in the all-sky survey or in the catalog of potential sources searched\(^5\). Because neutrinos pass undeviated through the whole cosmos, it is possible to have a situation where the observed sample of events is made up of one or two neutrinos from each of a large number of weak sources\(^5\). The situation may be quantified by comparing the flux from the whole sky (Eq. 1) with limits on the flux from a nearby source for each class of sources\(^5\),\(^5\),\(^5\). The flux from a nearby source at distance \(d\) is

\[
\phi_{\nu}^* \approx \frac{Q_{\nu}}{4\pi d^2} \approx Q_{\nu}\rho_0d. \tag{3}
\]

Typical upper limits on extragalactic sources in the seven-year point source catalog\(^5\) correspond to an energy flux \(< 2 \times 10^{-9}\) GeV cm\(^{-2}\)s\(^{-1}\). The product \(Q_{\nu}\rho_0\) in Eq. 3 is given by the observed diffuse flux from the last term of Eq. 1, so the point source upper limit \([3]\) implies an upper limit on the distance between sources and hence a lower limit on the density of sources. For an observed three-flavor neutrino energy flux of \(\sim 3 \times 10^{-8}\) in the units of Fig. 1, \(Q_{\nu}\rho_0 \sim 10^{43}\) erg/Mpc\(^3\) and the minimum source density is \(\sim 10^{-7}\) Mpc\(^{-3}\).

The combined constraints on density and luminosity of sources is displayed in a version of the Kowalski plot\(^5\) shown in Fig. 2. The solid line is the neutrino luminosity density \(Q_{\nu}\rho_0 \sim 10^{43}\) erg/Mpc\(^3\) and the broken line shows the power required for a neutrino efficiency of 1%. The equivalent analysis for bursting sources plots luminosity per burst vs density of bursts. It is interesting that some potential sources are marginally excluded by the minimum density requirement. In this situation, multi-messenger searches looking for coincidences in various ranges of the electromagnetic spectrum with neutrinos are of particular interest.
4 Real Time alerts from IceCube

In 2016 IceCube set up a real-time alert system. Any track-like event with sufficient energy to have a high probability of being an astrophysical neutrino generates an alert in the form of a public GCN circular within a minute of the event. About 10 alerts have been issued since the system began.

So far, only one case has led to a coincident observation of gamma-rays from the same direction, in this case a $\gamma$-ray flare identified by Fermi from a blazar TXS 0506+056. Higher energy $\gamma$-rays were also detected by MAGIC. The significance of these coincident observations is currently being assessed by all groups with relevant observations.

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