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Development of telescopes for extremely energetic neutrinos: AMANDA, ANITA, and ARIANNA

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ABSTRACT

Dedicated high-energy neutrino telescopes based on optical Cherenkov techniques have been scanning the cosmos for about a decade. At TeV scales, limits on the diffuse flux have improved by several orders of magnitude, eliminating the most optimistic models that tend to be normalized to the extragalactic X-ray or gamma-ray luminosity. At higher energies, neutrino telescopes have provided the first flux limits from point sources and diffusely distributed sources such as cosmogenic neutrinos generated by the GZK process, whose existence is relatively secure but whose predicted flux is frustratingly small. To substantially improve the experimental capabilities at the very highest energies, new techniques are required. I will briefly discuss preliminary results from the radio-based Cherenkov detector ANITA, and describe a new concept called ARIANNA that promises to increase the sensitivity to neutrinos with energies in excess of 10^{17} eV. Radio Cherenkov telescopes have already ruled out some of the more exotic predictions for neutrino intensity and may soon test more conventional GZK models. In addition to flux measurements, these devices can probe for non-standard particle physics by investigating the neutrino cross-section.

1. Introduction

The scientific promise of high-energy neutrino astronomy remains as compelling and elusive as ever. Although powerful neutrino telescopes such as AMANDA-II [1] and NT-200 [2] in Lake Baikal have uncovered no evidence for astrophysical neutrino sources, these first-generation detectors, optimized to detect neutrinos with energies between 10^{12} and 10^{15} eV, have paved the way for more capable telescopes with instrumented volumes as large as one cubic kilometer [3,4]. These detectors are based on the optical Cherenkov technique. During the past decade, the limit on the diffuse flux of neutrinos provided by the first generation of neutrino telescopes have improved by two orders of magnitude [5], and currently stand at $E^2(\mathrm{d}N/\mathrm{d}E)\sim 2\times 10^{-7}\,\mathrm{GeV/cm^2/s}$, summed over all ν-flavors. Equally noteworthy, the energy interval probe by these telescopes has been extended from $\sim 10^{12}$ eV to encompass energies between 10^{12} and 10^{18} eV. Similarly impressive improvements on the flux limits for point sources have been reported over the same period of time [5]. These results have ruled out most models of neutrino production that are connected to X-ray luminosities [6].

The existing diffuse flux limits can be used to gain further insight on the maximum flux expected from extragalactic (EG) point sources [7]. Section 2 discusses this intimate relationship and the robustness of the calculation.

At yet higher neutrino energies, new techniques were developed that detect *coherent* Cherenkov emission at *radio* wavelengths from high-energy neutrino interactions. This emission mechanism, known as the Askaryan effect [8], was experimentally confirmed less than a decade ago [9,10]. The balloon-borne ANITA payload and the South Pole based RICE array have exploited this effect to produce important constraints on the extraterrestrial neutrino flux.

About 40 years ago, Greisen, Zatsepin, and Kuzmin (GZK) predicted that the highest energy cosmic rays would rapidly lose energy by colliding with cosmic microwave background photons, thereby limiting the maximum energy that can be observed on Earth [11]. It was soon realized that high-energy neutrinos [12] were a natural by-product of these collisions, and these cosmogenic, also called GZK neutrinos, remain of one of the most secure predictions for a cosmic neutrino flux. Recently, the Auger [13] and HiRes [14] collaborations have reported strong evidence for GZK suppression in cosmic ray spectra, thereby increasing confidence in the existence of cosmogenic neutrinos. GZK neutrinos provide a powerful new tool to help understand the origins of the highest energy cosmic rays. For example, the neutrino energy spectrum helps to break model degeneracy between source distribution and evolution [15]. In addition, as discussed in Section 3.1, GZK neutrinos, may be used to probe for new physics at center-of-mass energies

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in excess of 100 TeV, significantly above the energy scale probed by LHC.

Unfortunately, the predicted flux of GZK ν is frustratingly small, and their observation requires new and radically different detector concepts. One such idea is called ANITA [16], a balloon-borne telescope that launched in December 2006 and circled high above Antarctica for about 35 days. It scanned for neutrino signals over an area larger than 1 million square kilometers. This and subsequent flights are expected to explore the sky at $E_\alpha > 10^{18.5}$ eV. Section 3 discusses the ANITA concept, outlines the calibration and verification procedures, and presents preliminary results including limits on the neutrino cross-section.

The RICE [17] detector, and more recently, AMANDA-II [18], Auger [19], and HiRes [20] have searched for neutrino emission in the intermediate energy regime between 10^{16} and 10^{18} eV (Fig. 2 displays several reported limits). The Auger ν_τ capabilities will improve with continued operation, and IceCube [3], will be completed by 2011. However, neither expect to measure more than a few GZK neutrinos per year. Therefore, a gap exists in the energy coverage of current-generation high-energy neutrino detectors.

To acquire sufficient statistics to definitively establish the existence of cosmogenic neutrinos, measure the full energy spectrum, and gain experimental insight on the neutrino cross-section at ultra-high energies (UHE), new concepts based on radio detection in salt domes (SALSA) [21] and Antarctic ice (AURA [22], IceRay [23], and ARIANNA [24]), and acoustic detection in salt, water, and ice media are under investigation [25,26]. It remains to be seen if any salt dome provides suitable radio attenuation characteristics [27], and current acoustic efforts are focused on technology development and baseline studies, such as characterizing the attenuation and ambient noise of the water and ice environments. ARIANNA, located only 150 km (~70 miles) from McMurdo Station, the primary supply hub of US Antarctic operations, utilizes the Ross Ice Shelf, whereas AURA and IceRay are located on the high Antarctic plateau at the Amundsen-Scott South Pole Station. IceRay, like ARIANNA, uses receivers buried near the surface, while AURA is based on the RICE concept of deeply buried linear dipoles.

2. Constraints on the EG point source flux

As previously discussed, no point sources of neutrino emission have been observed, making it difficult to establish much of anything concrete regarding the nature of the neutrino sources. They may or may not be correlated with the sources of EG cosmic rays. They may be correlated with the most powerful emitters of electromagnetic (EM) radiation in any band, or hidden from view of astronomical telescopes. Given the lack of experimental observation and the considerable variety of theoretical models and flux predictions, some insight on the flux from *point* sources may be gained from the experimental limits on the *diffuse* neutrino flux. If the diffuse n flux is generated by an ensemble of EG sources, then only the nearest would generate several neutrinos from the same direction, and therefore be detectable as distinct point sources. It is possible to compute a constraint on the flux from an EG point source based on the experimentally determined diffuse flux limit. First, we compute the number of detectable point sources, N_s, for a specified sensitivity to point sources and the known diffuse flux limit. By setting $N_s = 1$, the EG point flux constraint is obtained.

The calculation of N_s is based on three sensible assumptions:

1. EG ν sources are common, and uniformly distributed in space.
2. The luminosity distribution is characterized by a power (possibly broken) law.
3. Sources emit neutrinos with energy spectrum proportional to E^{-2}.

Of course, the matter density in the local universe is not uniform and if neutrino sources are traced by matter density, then this can impact the constraint. In Section 2.1, we discuss the degree of validity of these assumptions and caveats to the derived constraint.

Lipari [7] established that N_s is computed from the expression:

$$N_s \approx \frac{\sqrt{4\pi}}{3}\frac{1}{\sqrt{\ln(10)}}\frac{H_0}{c}\frac{K^{\text{diff}}}{(C_p)^{3/2}}\frac{\langle (L_\nu)^{3/2}\rangle}{\langle L_\nu\rangle}\frac{1}{\xi}$$

for an ensemble of sources that first "turn-on" at the Hubble radius, $d_H(=c/H_0 \sim 4\,\text{Gpc})$ and characterized by an arbitrary luminosity distribution, where L_ν is the ν_μ luminosity of the source per decade of energy, K_{diff} is related to the all-flavor diffuse flux limit by $K_{\text{diff}} = E^2(\mathrm{d}N/\mathrm{d}E)/3 = 5.6\times10^{-8}\,\text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ [5], valid for an energy spectrum proportional to E^{-2} over the energy interval of $10^{15}\,\text{eV} < E_\nu < 10^{18.5}\,\text{eV}$, and C_p is related to the instrumental ν_μ sensitivity to point sources with an assumed E^{-2} energy spectrum, so $C_p = E^2(\mathrm{d}N/\mathrm{d}E)$ $(\text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1})$. The effect of source evolution is governed by the parameter ξ, ranging between 0.5 and a few. It also slightly depends on assumed cosmology. For standard $\Lambda = 0.7$ cosmology, and source evolution as observed for AGN, then $\xi = 2.2$.

If the luminosity distribution of neutrino sources is characterized by a power law or broken power law (Assumption 2), which is commonly used to describe luminosity distributions in EM bands, then the expression for N_s simplifies to

$$N_s \approx \frac{\sqrt{4\pi}}{3}\frac{1}{\sqrt{\ln(10)}}\frac{H_0}{c}\frac{K^{\text{diff}}}{(C_p)^{3/2}}\frac{\langle L_\nu\rangle^{1/2}}{\xi} \tag{1}$$

which indicates that N_s can be computed from the mean luminosity of the source distribution, and implies that the brighter sources are too rare to significantly alter the naïve expectation that the most likely source detected will have average intrinsic luminosity.

Using the 5-year AMANDA-II point source limit [29] to estimate the detector point sensitivity for E^{-2} spectra, giving $C_p = 5\times10^{-8}\,\text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1}$, we find $N_s = 0.06(L_\nu/L_{45})^{1/2}$, where the mean neutrino luminosity is scaled to $10^{45}\,\text{erg}\,\text{s}^{-1}$ per decade $(=L_{45})$, a convenient value that characterizes AGN X-ray luminosities. We note that $N_s \ll 1$ is compatible with the non-observation of neutrino point sources by AMANDA-II.

The point flux constraint is obtained by setting $N_s = 1$ and solving for C_p, giving [5]

$$E^2(\mathrm{d}N/\mathrm{d}E) \leqslant 8.2\times10^{-9}(L_\nu/L_{45})^{1/3}\ \text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1} \tag{2}$$

This constraint, valid for the energy interval $10^{15}\,\text{eV} < E_\nu < 10^{18.5}$ eV, is a factor of six more stringent than current experimental limits, and excludes a variety of models as shown in Fig. 1. A similar constraint can be calculated from the VHE diffuse limit [28] and indicated in the region labeled "VHE Flux Constraint" in Fig. 1. The lower boundary of the constraint bands are computed for weaker sources, characterized by $L_\nu = 10^{40}\,\text{erg}\,\text{s}^{-1}$ per decade. Also note that the constraint applies to sources that are highly beamed and/or time variable, such as GRBs, if L_ν is the *observed* mean luminosity per decade of the source distribution. However, since the observed optical (and predicted neutrino) luminosities for GRBs is of order $10^{51}\,\text{erg}\,\text{s}^{-1}$, more restrictive flux limits are obtained from dedicated searches [30].

Within the next year, it is expected that the AMANDA-II UHE diffuse analysis based on TWR technology will include data from 2004 to 2005, increasing the live-time by roughly a factor of 3, further improving the sensitivity. From Eq. (1), it can be seen that