STATUS OF ANITA AND ANITA-LITE

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Abstract We describe a new experiment to search for neutrinos with energies above $3 \times 10^{18}$ eV based on the observation of short duration radio pulses that are emitted from neutrino-initiated cascades. The primary objective of the ANtarctic Impulse Transient Antenna (ANITA) mission is to measure the flux of Greisen-Zatsepin-Kuzmin (GZK) neutrinos and search for neutrinos from Active Galactic Nuclei (AGN). We present first results obtained from the successful launch of a 2-antenna prototype instrument (called ANITA-lite) that circled Antarctica for 18 days during the 03/04 Antarctic campaign and show preliminary results from attenuation length studies of electromagnetic waves at radio frequencies in Antarctic ice. The ANITA detector is funded by NASA, and the first flight is scheduled for December 2006.

Keywords: High Energy Neutrinos, Neutrino Telescopes, Neutrino Astronomy, Antarctic Ice Attenuation, GZK Neutrinos, Radio Detection, ANITA

Introduction

ANITA is designed to search for particles that are created in the most powerful environments in the universe. Its primary goal is to discover neutrinos gen-
erated by interactions between the highest energy cosmic rays and the cosmic microwave background radiation, as well as neutrinos created at the inner edge of supermassive black holes (SMBH). Flying at an altitude between 35-40 km above the Antarctic continent, the ANITA balloon-borne telescope will be sensitive to a target volume of $\sim 10^6 \text{ km}^3$ of radio-transparent ice. The aperture of ANITA exceeds $\sim 100 \text{ km}^3\cdot\text{sr}$ at $E_\nu = 3 \times 10^{18} \text{ eV}$, averaged over neutrino flavor and assuming equal fluxes of all flavors. The aperture continues to grow rapidly as $E_\nu$ increases, reaching the order of $10^5 \text{ km}^3\cdot\text{sr}$ at $E_\nu = 10^{21} \text{ eV}$. At EeV energies, the Earth is opaque to neutrinos so only horizontal or slightly downgoing neutrinos are detectable (Fig. 1). Neutrinos interact within the ice and generate compact particle showers, which emit coherent radio signals that are detectable in the radio-quiet environment of the Antarctic continent.

1. **Science Goals**

**Standard Sources.** High Energy neutrinos carry unique information from objects in the universe, and complement the information provided by UHE $\gamma$-ray astronomy. For example, neutrinos, unlike photons, can propagate throughout the universe unattenuated, but photon astronomy between 10-100 TeV is limited to distances less than a few hundred Mpc due to interactions with infrared background photons, and to even shorter distances at PeV energies due to interactions with the cosmic microwave background. Neutrinos may be the only method to shed light on acceleration processes associated with sources of the highest energy cosmic rays, which extend more than six orders of magnitude above energy of 100 TeV. Thus, the direct detection of high energy neutrinos (Stecker, 1968, Berezinsky and Zatsepin, 1969, Stanew, 2004) will complement the investigation of the GZK cutoff (Greisen, 1966, Zatsepin and Kuzmin, 1966, Kuzmin, 2004), one of the most controversial issues in cosmic ray physics.

Several theoretical models predict neutrino emission related to accreting SMBH, which arise from particle acceleration near the black hole at the center of AGN (Mannheim et al., 2001). In this environment ultra-high energy protons may escape from the source, and a fraction of them eventually interact to produce high energy neutrinos. Therefore, high-energy cosmic-ray observations can be used to set a model-independent upper bound on the high-energy neutrino flux (Waxmann and Bahcall, 1999).

**Physics beyond the Standard Model.** The ANITA science goals extend beyond the Standard Model if GZK neutrinos produce highly unstable micro black holes (BH) when they interact with ice (Feng and Shapere, 2002, Alvarez-Muniz et al., 2002). The decay of these highly unstable micro BH via Hawking radiation would generate energetic hadronic showers that ANITA would detect. The signature of such events is the observation of an enhanced detection rate
that is strongly energy dependent. This observation would provide evidence of new phenomena, such as the existence of extra dimensions.

2. ANITA

The Concept. The concept of detecting high energy particles through coherent radio emission was first postulated by Askaryan (Askaryan, 1962) and has recently been confirmed in accelerator experiments (Saltzberg et al., 2001). Particle cascades induced by neutrinos in Antarctic ice are very compact, no more than a few centimeters in lateral extent (Zas et al., 1992). The resulting radio emission is coherent Cherenkov radiation which is characterized by a conical emission geometry, broadband frequency content, and linear polarization. ANITA (Barwick et al., 2003a) will observe the Antarctic ice sheet out to a horizon approaching 700 km, monitoring a neutrino detection volume of order $10^6$ km$^3$. The direction to the event is measured by time differences between antennas in the upper and lower clusters (Fig. 2). The statistical distribution of events should correlate with ice thickness, averaged over observable volume. As illustrated in Fig. 1, ANITA will search for radio pulses that arise from electromagnetic and hadronic cascades within the ice. The signals propagate through 1-3 km of ice with little attenuation. At the energies of relevance to ANITA, the Earth strongly attenuates the neutrino flux, so ANITA is primarily sensitive to horizontal neutrinos. A radio pulse with zenith angle $< 34^\circ$ will refract through the air-ice interface and may be observed by ANITA. Refraction
and reflection effects due to small variations of the index of refraction in the layered structure of Antarctic ice are modest for the relevant incident angles. The RF emission pattern is peaked in a forward conical geometry, but considerable power remains within $5^\circ$ of the Cherenkov cone. At ANITA energies, cascades initiated by electrons (e.g. in $\nu_e$ charged current events) are altered by LPM (Landau and Pomeranchuk, 1953, Migdal, 1957) effects which narrows the width of the Cherenkov Cone pattern to considerably less than $5^\circ$. Cascades initiated by recoil hadrons are not affected, and provide the bulk of observable events for neutrino energies above 1 EeV (Alvarez-Muniz and Zas, 1998).

**Effect of Non-uniform Snow Surface.** The ANITA team is investigating the effect of surface features on signal characteristics. Surface structures that are somewhat larger than the wavelength band of the Cherenkov pulse, such as sastrugi, occupy only a small fraction of the surface. Random small-scale features are not expected to produce significant variations from average behavior. While the visual impact of surface roughness is quite apparent, the density contrast (and gradient of index of refraction) is only 10-30%. The broadband characteristics of the Cherenkov pulse also tend to mitigate amplitude variation due to interference. An event located at a typical depth of 1 km produces a coherent patch on the surface of $\sim 30$ m in radius for the frequencies of interest. We have performed an analytic treatment of the air interface, assuming Gaussian fluctuations for the depth of snow, and find that the loss of phase coherence at the antenna reduces the detected power by less than 5%. We are pursuing the use of optics analysis software to numerically study surface effects.

**The Detector.** The ANITA instrument (Barwick et al., 2003b), shown in Fig. 2, is a cluster of broadband quad-ridged horn antennas with a frequency range from 0.2 to 1.2 GHz. The beam width of the antenna is about $60^\circ$, with a gain of approximately 9 dBi at 300MHz; gain is roughly constant across the entire band. The detector geometry is defined by a cylindrically symmetric array of 2 levels of 8 antennas each on the upper portion, with a downward cant of about $10^\circ$, to achieve complete coverage of the horizon down to within $40^\circ$ of the nadir. The antenna beams overlap, giving redundant coverage in the horizontal plane. A second array of 16 antennas on the lower portion of the payload provides a vertical baseline for time delay measurements which will determine pulse direction in elevation angle. The absolute azimuthal orientation is established by Sun sensors, and payload tilt is measured by differential GPS.

3. **ANITA-lite**

A two-antenna prototype of ANITA, called ANITA-lite, was flown for 18 days on a Long-Duration Balloon (LDB). It was launched on December 17,
2003 as a piggyback instrument onboard the Trans-Iron Galactic Element Recorder (TIGER) (Link et al., 2003). Both polarizations of each quad-ridged horn antenna were digitized. For the purpose of triggering, the four linear polarization channels were converted to right-handed and left-handed circular polarization for a total of four channels. The trigger criteria required that 3 of 4 waveforms exceed a specified voltage threshold, which varied throughout the flight. The ANITA-lite mission tested nearly every subsystem of ANITA, and monitored the Antarctic continent for impulsive Radio Frequency Interference (RFI) and ambient thermal noise levels as well as triggered events. We discuss a few results that impact the upcoming ANITA experiment.

**Timing Analysis Results.** While aloft, ANITA-lite received signals from a surface transmitter to measure the timing resolution. Signals were observed out to distances of 200 km. The waveforms were processed by digital filtering of the frequency components (Silvestri, 2004), and the results of a band-pass filter applied to the raw waveform can be seen in Fig. 3. The time reference for each antenna was extracted by interpolating the zero-crossing of a signal that exceeds \(4V_{\text{rms}}\), where \(V_{\text{rms}}\) is the rms fluctuation of the noise voltage (Nam, 2004). The uncertainty in the time difference between the copolarized channels of both antennas flown on ANITA-lite was \(\sigma_{\Delta t} = 0.16\) ns (see Fig. 4) after correction for azimuthal variation. This value is based on the full set of calibration events that were acquired over a range of 40° in zenith angle \(\theta\), indicating that the systematic dependence of timing on \(\theta\) is rather weak.

For ANITA, we expect the time resolution between antenna clusters to improve to \(\sigma_{\Delta t} = 0.1\) ns due to the increase in the number of measurements by the full array. Using 3.3 m vertical separation between the upper and lower
antenna arrays, \(d\), the expected intrinsic zenith angle resolution \(\sigma_\theta\) is

\[
\sigma_\theta = (\sigma_{\Delta t} \frac{c}{d} 57.3^\circ) = 0.5^\circ
\]  

(1)

for events near the horizon. Similarly, azimuthal angular resolution \(\sigma_\phi\) is estimated to be \(1.5^\circ\) using the \(\sim 1\) m baseline separation between antenna elements in a ring.

**Thermal Noise Analysis Results.** Another goal of Anita-lite was to investigate the level of ambient broadband noise in Antarctica at the balloon altitude and relate it to the absolute thermal noise background. Cosmic background radiation combined with the Galactic radio noise contributes noise of the order of 10-50K, and the average temperature of the Antarctic ice surface is in the range of 220-250K. The contribution of the Sun at 0.2-1.2 GHz is between \(10^5\) to \(10^6\) K depending on solar activity and radio frequency, however, its angular size in the radio band is of order \(1^\circ\) so its contribution is comparable to the Galaxy when averaged over the angular acceptance of the antenna. Both the Sun and the brightest region of the Galaxy were within the same field of view during the ANITA-lite flight. The results of this analysis are shown in Fig. 5,

\[\text{Figure 5. ANITA-lite calibration sources - Sun and Galaxy - thermal measurements as a function of angle with respect to the Sun during the 18 day flight.}\]

\[\text{Figure 6. Examples of ANITA-lite interference events (top 4 panes) and two views of an injected signal-like impulse (bottom panes).}\]

where a clear excess of power in the solar direction is seen, consistent with the expectation (Miocinovic et al., 2004). This conclusion is encouraging for ANITA since it shows that the measured RF noise is consistent with expected noise levels.
Impulse Noise Analysis Results. ANITA-lite measured about 130,000 distinct events, with an approximate rate of 5 events per minute. Fig. 6 shows examples of the major classes of impulsive noise encountered. The vast majority of triggered events are due to local payload interference such as switching noise from the Support Instrument Package. The duration of this class of events exceeds several hundred nanoseconds and a few events exhibit circular polarization for a portion of the pulse. The bottom two panes show an example of a synthetic pulse injected into the data stream to simulate a true signal event. The pulse is coherent and aligned across all channels. Preliminary studies of event selection procedures were conducted. They yield no passing events, while 97% of simulated Askaryan-induced impulses with amplitude $5\sigma$ above noise survive (Miocinovic et al., 2004).

4. Attenuation Studies of Antarctic Ice

The attenuation length of the ice beneath the South Pole Station was measured in 2004 (Barwick et al., 2004). A pair of broadband Ultra-High Frequency (UHF) horns, with range from 200 to 700 MHz, were used to make echograms by reflecting radar pulses off the bottom of the ice cap (depth 2810 m), and measuring the return amplitude in a separate receiver. Antarctic ice exhibits a horizontally layered structure, which creates small variations in the index of refraction. The near vertical penetration of the radio signal through the ice strata minimizes the impact of reflections due to variation of the index refraction. By making the assumption that the reflection coefficient off the bottom is unity, one can derive a lower limit on the attenuation length. Because of the logarithmic dependence of the derived attenuation length on most of the parameters, the uncertainty in the attenuation length is relatively small. A summary of the results is shown in Fig. 7, where the error bars are an estimate of the $2\sigma$ systematic errors such as uncertainty in temperature profile of the ice, reflection coefficient, and antenna responses. The radio pulse propagates through ice which varies from $-50^\circ$C at the surface to near $0^\circ$C at the bottom. We correct the results to $-45^\circ$C, a typical temperature for Antarctic ice. At this temperature the field attenuation length is $\geq 1$ km between 200-700 MHz. These encouraging results define one of the most fundamental physical properties necessary for the success of ANITA.

5. ANITA Sensitivity

Fig. 8 shows various neutrino models, experimental limits, and a recent (late 2004) estimate of the sensitivity of ANITA for the baseline 3 LDB flights. ANITA will achieve $\sim 2$ orders of magnitude improvement over existing limits on neutrino fluxes in the relevant energy regime. Assuming a 67% exposure over deep ice, typical of an LDB flight, we expect between 5-15 events from
standard model GZK fluxes (Engel et al., 2001, Protheroe and Stanev, 1996), with the uncertainty primarily arising from assumptions about cosmic ray source evolution. Conversely, an observation of no events would reject all standard GZK models at the $\geq 99\%$ C.L. We stress that the GZK neutrino fluxes shown are predictions of great importance to both high energy physics and our understanding of cosmic-ray production and propagation. A non-detection of these fluxes by ANITA would suggest non-standard phenomena in either particle physics or the astrophysics of cosmic ray propagation.

6. Conclusion

ANITA will use radio emission from the cascade induced by a neutrino interaction within the Antarctic ice cap to detect UHE neutrino interactions that occur within a million square km area. The remarkable transparency of Antarctic ice to radio waves makes this experiment possible, and the enormous volume of ice that can be simultaneously monitored leads to an unparalleled sensitivity to neutrinos in the energy range of 0.1 to 100 EeV. Three separate flights provide 45 days of livetime, which can be increased by multiple orbits around the South Pole. It is possible, under optimal conditions and the use of multiple orbits around Antarctica, to obtain an integrated livetime approaching

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure7.png}
\caption{Field attenuation length versus radio frequency for 2004 measurements at the South Pole.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure8.png}
\caption{Neutrino models and experimental limits (90\% C.L.) along with a recent estimate single-event sensitivity per energy decade of ANITA for the baseline mission of 3 flights that achieve 45 days of total exposure, assuming that ice is observable from ANITA payload 67\% of the time.}
\end{figure}
100 days. In December 2001 the TIGER instrument obtained a record 31.8 day flight by circling twice around the Antarctic continent. Even the first ANITA flight will constrain model predictions of GZK neutrino fluxes and provide insight to particle physics at the energy frontier.

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