29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

Radio Detection of UHE Neutrinos with the Antarctic Impulsive Transient Antenna (ANITA) Experiment: Data and Analysis

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The ANITA experiment is a balloon-borne radio-pulse detector system designed to measure Ultra-High Energy (UHE) neutrinos interacting in the Antarctic ice utilizing the distinct broadband radio pulse due to the Askaryan effect. The radio-transparent ice serves as a target volume for the production of these pulses. ANITA will have an effective viewing area of over one million km^2 of ice at float altitude (~37 km). A prototype experiment, ANITA-LITE, was flown during the 2003-2004 Austral Summer from Antarctica to perform an impulsive RF background survey of Antarctica. In the process, it has yielded strong constraints on UHE neutrinos, ruling out some theoretical models. We also discuss the expected instrument performance for the first full ANITA flight, planned for a 2006 Austral Summer launch out of McMurdo, Antarctica.

1. Introduction

Cosmic rays with energies about a few times 10^{19} eV are nearly certainly of extragalactic origin as their gyroradii exceed the size of the Galaxy. At these energy scales, pion photoproduction losses through interactions with the Cosmic Microwave Background Radiation (CMBR), the Greisen-Zatsepin-Kuzmin (GZK) process, limit cosmic-ray propagation distances to the local supercluster.[1] Within this distance, about 40-50 Mpc, there are no known sources yet discovered, and the cosmic-ray spectrum does not show a convincing GZK cutoff. Experiments to resolve these uncertainties by directly examining the cosmic-ray flux up to and beyond 10^{20} eV are ongoing using multiple detector techniques.[2]

Another way to examine the UHE universe is through neutrinos. Unlike the cosmic-ray nuclei, neutrinos are not subject to deflection by magnetic fields or interactions with the CMBR and thus should point back to their source even at cosmological distances. In the GZK process, a guaranteed source of UHE neutrinos is produced and additionally there may exist point sources of UHE neutrinos such as black hole accretion disks, AGNs or the gamma-ray bursts. Measurements of the neutrino spectrum at high energy can therefore shed light on the UHE universe or, if no UHE neutrinos are detected, reveal violations of standard models of physics and cosmology governing the observed UHE particles. Directly detecting these neutrino showers is difficult due to their low fluence and small interaction cross-sections, however.

The ANITA experiment exploits a property of electromagnetic (EM) cascades known as the Askaryan Effect.[3] Though first noted in the 1960s, this strong coherent Cherenkov emission from a shower in a dense material was not measured until this past decade.[4] Selective electron scattering processes in the shower give rise to a charge imbalance producing a uniquely characteristic broadband pulse. In the radio-transparent Antarctic ice, this signal has an attenuation length greater than 1 km in the few hundreds of MHz frequency range.[5] These signals can be observed from a high-altitude balloon detector system flying over Antarctica as shown in Figure 1. More on the detector systems can be found elsewhere.[6]

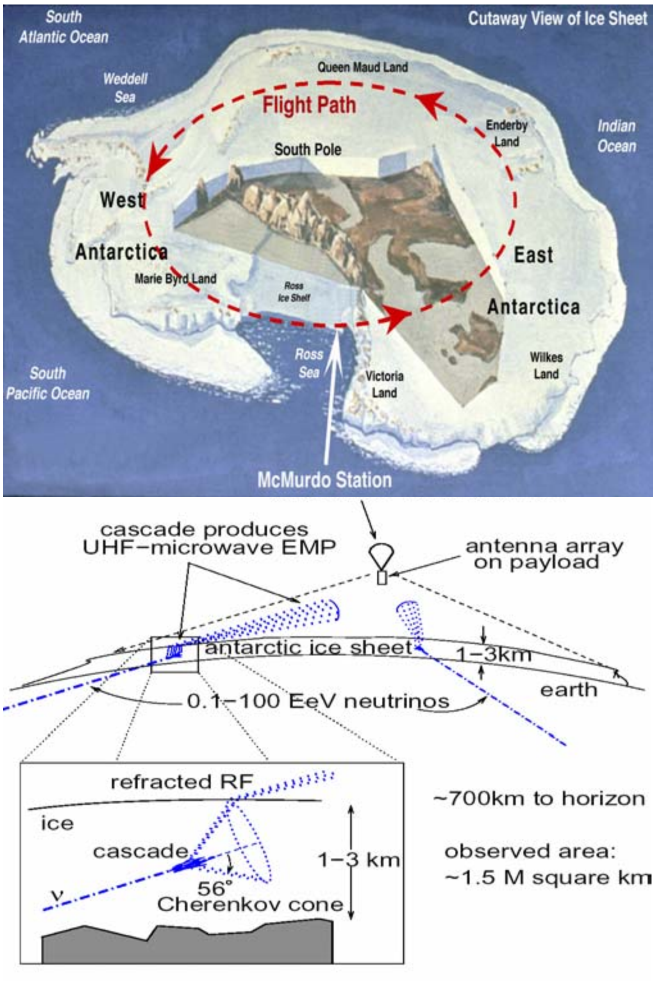

Figure 1. Top: Flight path and instanteous aperature on the ice. Bottom: Geometry of the EM cascade to balloon path.

2. ANITA-LITE Data and Analysis

The ANITA prototype and background measuring experiment, ANITA-LITE, flew from McMurdo, Antarctica from 17 December 2003 through 4 January 2004 on a high-altitude balloon piggyback on the TIGER cosmic-ray instrument. This test flight is described in more detail elsewhere[7], but analysis has shown no broadband impulsive events (two independent analyses) due to either Askaryan conditions or anthromorphic background. Although this flight used only two dual-polarization quad-ridge horns (out of 40 for the full payload), and primarily commercial electronics, ANITA-LITE still viewed an enormous volume of Antarctic ice and led to the strongest current limit on neutrino fluxes in this energy range. There were 16.2 days of analyzed data with a net livetime fraction of about 40%, with the lost livetime due to locally produced EMI. Ice depth and coverage for the flight path were included. This resulting limit on UHE neutrinos is an interesting and unplanned science bonus from this test flight.

Prior experiments looking for UHE neutrinos have included the RICE radio array at the South Pole (which also utilizes the Askaryan Effect, though observed *in situ* in the ice), the GLUE effort looking for Askaryan pulses from the limb of the lunar regolith with radio telescopes, the AMANDA optical Cherenkov measurements at lower energies (a South Pole *in situ* experiment), and the FORTE radio-pulse observing satellite. Three days of FORTE data taken over the Greenland ice sheet were searched for Askaryan-like signals. Their exclusion limits, along with the ANITA-LITE limit, are shown in Figure 2.

Two sets of theoretical results are also shown in Figure 2. Those are the band of model expectations of neutrinos produced from cosmic-ray nuclei through the GZK process—with the uncertainties due to somewhat experimentally incompatible UHE cosmic- ray observations, and the acceptable range of models for the source distribution and evolution, and the predictions of three so-called Z-burst models.[8] These high-energy cosmogenic models of resonant neutrino annihilation are completely ruled out—they predicted 20-30 neutrino events to be observed in ANITA-LITE. The Z-burst models are shown as crosses on the figure with error bars representing the range of allowed model parameters. Other limits, such as on the scale size of large extra dimensions, are still being evaluated.

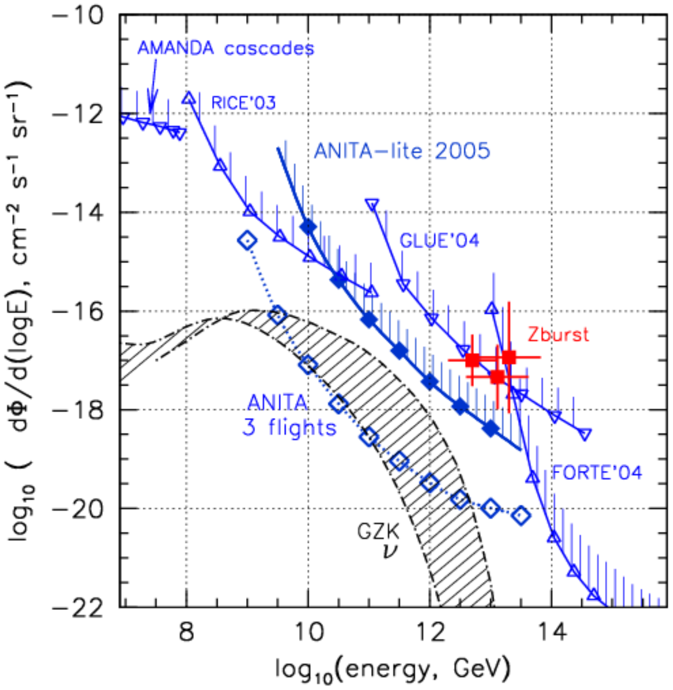

Figure 2. UHE neutrino limits, model predictions, and a calculation for the null-observation limit from three ANITA flights.

3. ANITA Performance Expectations

The ANITA experiment is under construction, and will have a test flight for engineering purposes from Fort Sumner, New Mexico, USA in 2005. Its first Antarctic flight is planned for Austral Summer (Dec-Jan) of 2006-2007. This is the first of three planned science flights that have as their primary science goal the measurement of the GZK neutrinos, with adequate statistics to allow for an understanding of the UHE cosmic rays, and the detection of any additional sources of UHE neutrinos in this energy range. The expected sensitivity of three average Long-Duration Balloon (LDB) flights (15 days each) is shown in Figure 2 as "ANITA 3 flights." The goal of 45 days may take fewer than three flights; *e.g.*, the 2004-2005 flight of the CREAM experiment (LDB) was 42 days long.

The total volumetric aperture of the ANITA instrument is shown in Figure 3 along with a comparison to the aperture and energy reach of the IceCube experiment under construction at the South Pole. It is clear that the two experiments, with very different detector techniques and very different science goals, are actually quite compatible in energy scale and aperture. Both experiments use the Antarctic ice as a radiator. 1 km^3 of South Pole ice for IceCube and about 1 million km^3 of ice sheet for ANITA are used, but the latter is viewed from a greater distance (~700km to the horizon).

The ANITA and ANITA-LITE aperture and sensitivity limits have been calculated using two independent and mature Monte Carlo simulations. These simulations account for neutrino propagation through rock and ice in an Earth-crust model, for various interactions and

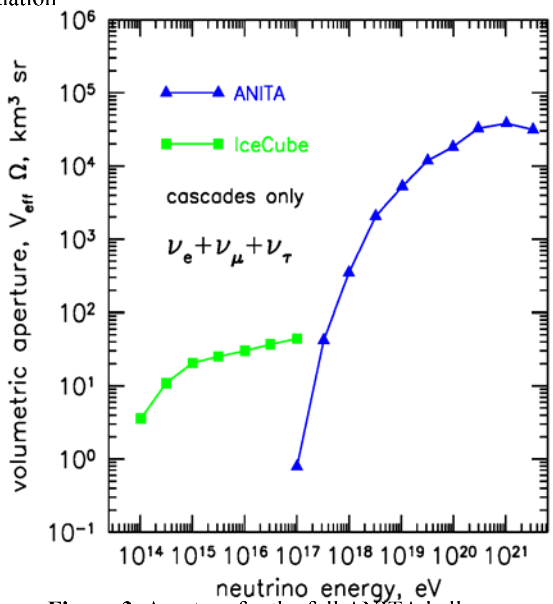

Figure 3. Aperture for the full ANITA balloon experiment and the IceCube detector is shown.

neutrino flavors, for inelasticity, and both EM and hadronic cascades (including Landau-Pomeranchuck-Migdal (LPM) effects). Radio emission is calculated

from parameterizations tested with accelerator data. RF propagation through the ice is modeled with a frequency and temperature-dependent attenuation length, verified by South Pole ice measurements.[5] Surface refraction is handled with a facet model while local and global surface roughness spectra are based on traverse measurements. Refracted emission is propagated geometrically to the payload where a detailed model of the time and frequency response of the antennas and electronics determine whether a trigger occurs.

4. Conclusions

Although it was designed primarily as a backgrounds-measuring test payload, ANITA-LITE has improved limits on UHE neutrinos above 10^{20} eV by more than an order of magnitude over the GLUE results.[9] This has demonstrated the power of the Askaryan, radio-Cherenkov, technique applied from balloon-borne detectors over the Antarctic continent. Z-burst models, as they currently exist, are completely excluded by this limit.

ANITA simulations show another order of magnitude improvement in sensitivity and an order of magnitude lower energy threshold. This is sufficient, with on order of 45 days of balloon flight averaging over various depths and coverage of Antarctic ice, to constrain or detect all current GZK neutrino models and the majority of "exotic" neutrino models.

Beyond the ANITA balloon flights, the possibilities of "station-keeping" permanent or semi-permanent RF pulse-detecting systems above the Antarctic ice have been examined. These present significant technical difficulties, but the first GZK neutrino detections may well stimulate effort in this area. The possibilities of using salt domes, high-purity mushroom-shaped geological salt extrusions, with *in situ* detectors have also been examined with the goal of an instrumented teraton detector for UHE neutrinos. This project, SalSA, is in the early planning stages.[10]

5. Acknowledgements

This work is supported by the National Aeronautics and Space Administration. We thank the National Science Foundation and the National Scientific Balloon Facility for their excellent support of the Antarctic balloon campaign and flight of ANITA-LITE.

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