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Observation of an Unusual Upward-Going Cosmic-Ray-like Event in the Third Flight of ANITA

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We report on an upward traveling, radio-detected cosmic-ray-like impulsive event with characteristics closely matching an extensive air shower. This event, observed in the third flight of the Antarctic Impulsive Transient Antenna (ANITA), a NASA-sponsored long-duration balloon payload, is consistent with a similar event reported in a previous flight. These events could be produced by the atmospheric decay of an upward-propagating τ lepton produced by a ν_τ interaction, although their relatively steep arrival angles create tension with the standard model neutrino cross section. Each of the two events have *a posteriori* background estimates of $\lesssim 10^{-2}$ events. If these are generated by τ-lepton decay, then either the charged-current ν_τ cross section is suppressed at EeV energies, or the events arise at moments when the peak flux of a transient neutrino source was much larger than the typical expected cosmogenic background neutrinos.

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The ANITA instrument is primarily designed for the detection of the ultrahigh energy (UHE) cosmogenic neutrino flux via the Askaryan effect in ice [1–3], but is able to trigger on a wide variety of impulsive radio signals. During the first ANITA flight, 16 unexpected events due to an ultrahigh energy cosmic ray (UHECR) extensive air shower (EAS) were found during a blind search for isolated nonanthropogenic events [4]. ANITA observes UHECR via radio impulses that occur when geomagnetically induced, charged-particle acceleration occurs in the propagation of an EAS in the atmosphere. Conventional down-going UHECR extensive air showers produce downward-propagating radio impulses that are observed in reflection off the surface of the ice, leading to phase inversion of the waveform, flipping the polarity [5]. UHECR events detected by ANITA also include a subset of horizontally propagating stratospheric extensive air showers seen just above the horizon, which point directly at the payload, and show no phase inversion of the waveform [6]. These observations have established a baseline for identification of events of UHECR origin in ANITA data.

In the ANITA-I flight, one such UHECR-like event was observed with characteristics similar to the direct, horizontal cosmic rays, but from a direction well below the horizon, without the phase inversion due to a reflection [6]. The estimated chance anthropogenic background

was $\leq 10^{-3}$ events, leading us to consider whether it could arise from a high-energy charged-current neutrino interaction in the ice, producing a lepton that exits the ice surface and decays or interacts. Electrons from ν_e interactions shower within tens of meters range in ice, and muons from ν_μ interactions at these energies have decay lifetimes of hours; thus τ leptons from ν_τ interactions, with a decay length of order 10 km, are far more probable for a roughly equally flavor-mixed neutrino flux [7,8]. The resulting lepton decay then produces an EAS that propagates upward in the atmosphere. This single event, the only one found in the ANITA-I data, was not by itself adequate to confirm this possibility.

The third flight of the ANITA instrument took place from December 18, 2014 to January 8, 2015, with 22 days at float at an altitude of ∼34–38 km. Unexpected strong continuous-wave interference from geosynchronous satellites limited the effective full-payload exposure to about seven days of equivalent time. Despite this loss of sensitivity, a set of 20 radio-detected UHECR events were identified in a template-based analysis [9]. Because phase-inversion was the primary characteristic that would distinguish reflected events from direct events, including possible upward-going extensive air showers, we blinded our analysis to the event polarity throughout the analysis to avoid bias. The geomagnetic field in Antarctica is predominantly vertical, and thus the Lorentz-force acceleration of the e^+e^- pairs in the shower leads to lateral charge separation that produces an almost completely horizontally polarized (HPOL) signal, with very distinct temporal and spectral properties compared to anthropogenic background events observed. Despite their small size, the residual horizontal components of the geomagnetic field still provide for a detailed confirmation of the geomagnetic correlation of UHECRs. Unlike midlatitudes [10], very large transient atmospheric electric fields (such as caused by convective cloud formation) are unknown over Antarctica, and deviations in the ambient dc electric field due to driven snow or strong winds are not large enough to affect these results [11].

In a local Cartesian basis, the geomagnetic field $\mathbf{B} = (B_x, B_y, B_z)$ satisfies $B_x, B_y \ll B_z$ as noted above. ANITA's observation geometry also favors EAS with primary particle momenta with zenith angles of 60° or more, and thus their longitudinal velocity will follow $v_x, v_y \gg v_z$ in general. From Feynman's rule [12], the radiation field per particle will be aligned with the observer's apparent angular acceleration of the charge, which is given by the magnetic portion of the Lorentz force, $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$. Neglecting terms that are second order in the acceleration, and recognizing that the magnetic deflection is nearly perpendicular to the direction of radiation, the observed radiation field vector satisfies $\mathbf{E} \propto (v_y B_z \hat{x} - v_x B_z \hat{y}) + (v_x B_y - v_y B_x)\hat{z}$. The first term in parentheses on the right-hand side gives the HPOL component of the field, and because it involves the strongest components of both $\mathbf{v}$ and $\mathbf{B}$, it is the much stronger of the two radiation fields. The second term gives the vertically polarized (VPOL) field component, and is significantly weaker because it depends on the much weaker transverse magnetic field vector components.

In addition, there is a small contribution from Askaryan emission, but because of the strong Antarctic geomagnetic field, this is limited to about 4% of the total [13–15] and is neglected here. Because ANITA is designed to do accurate pulse-phase polarimetry with both HPOL and VPOL receiving antennas, the transverse B-field component is readily detectable. Since the geomagnetic field is well modeled in Antarctica, it provides a strong confirmation of geomagnetic association for a given UHECR impulse, whereas signals of anthropogenic origin are uncorrelated to the geomagnetic field. Figure 1 shows the geomagnetic-correlated results for the UHECR events selected in ANITA-III, The expected polarization is corrected for the Fresnel coefficient of reflection where appropriate. Measurement errors were determined directly from the data and include systematics.

The unblinded polarity of the ANITA-III CR events showed that the two above-horizon events among the sample had the expected noninverted pulse phase, consistent with their origin as stratospheric, atmosphere-skimming extensive air showers. However, as noted above, one of the remaining events also had a clearly noninverted polarity, inconsistent with a reflection, but in all other ways consistent with UHECR origin. Figure 2 shows the
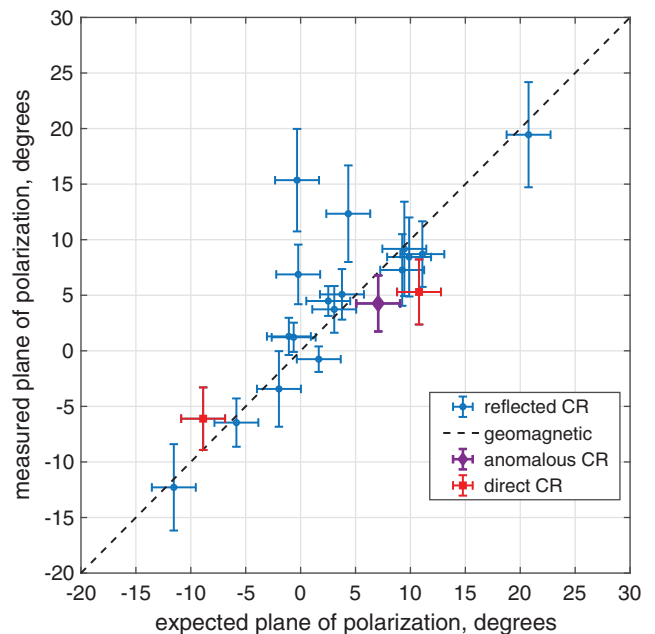

FIG. 1. Geomagnetic correlation of 20 UHECR events detected in ANITA-III, with event planes of polarization determined via Stokes parameters for each event. The two above-horizon non-inverted CRs are shown in red, and the anomalous noninverted, below-horizon CR-like event 15717147 is shown in magenta.
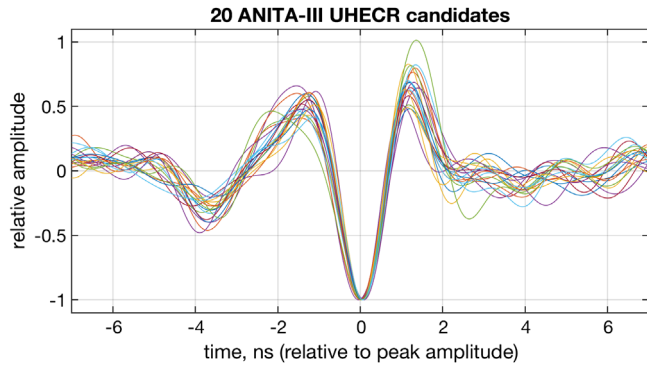
FIG. 2. Horizontally polarized waveforms of 20 UHECR events detected in ANITA-III, with amplitudes all normalized to their peaks. The 17 reflected CRs have been flipped to match the noninverted polarity.
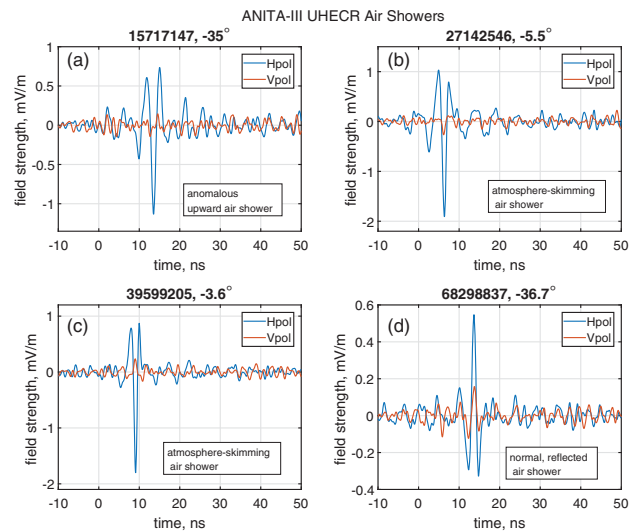

FIG. 3. The three noninverted polarity events are shown in panels (a), (b), and (c). Panel (a) shows the anomalous event, with the same polarity as the above-horizon events (b) and (c). Panel (d) shows the waveform for an inverted UHECR that had an upcoming angle close to that of the anomalous CR 15717147. The inversion of the normal reflected CR event is clearly evident.

overlain normalized HPOL waveforms from each of the 20 candidate events, with the 17 inverted-polarity reflected events now uninverted for direct comparison of the waveform shape. The events have the instrumental response deconvolved, and are normalized in amplitude to their maximum magnitude. They are remarkably similar in shape once the inversion is removed.

For the final 20-event UHECR selection, candidates were verified to be spatially and temporally isolated from any other events like them, and showed a high degree of correlation with a waveform template determined by well-established models for UHECR radio emission. We have identified no known physics backgrounds for these events. Potential background comes from anthropogenic radio signals that might mimic the UHECR characteristics, or unknown processes that might lead to noninverted polarity on reflection from the ice; further investigation of polarity is given in Ref. [16]. Two independent background estimates for anthropogenic origin were made. The first, using the likelihood that the event was a statistical outlier of subthreshold events within its nearby locale, gave a background estimate of $B = 1.2 \times 10^{-3}$ events for the 20-UHECR sample [9]. The second method uses a probability for a single isolated UHECR-like background event, derived from the frequency of UHECR-like events that appeared in known anthropogenic clusters of events and charted bases or camps. Because the rate of actual UHECR events is such that some inevitably do get included (and therefore lost to the analysis) as part of these clusters, this latter estimate provides only an upper limit to the background, $B \leq 3 \times 10^{-3}$ events for the entire 20 UHECR sample [16]. Thus by all indications the resulting selection of events represents a very pure sample of radio-detected UHECRs.

Figure 3 shows the incident field strength waveforms for all three of the events with noninverted polarity, along with one of the "normal" UHECR events, chosen because its arrival angle at the payload was similar to that of the

anomalous event 15717147. Using methods we have applied to our other radio-detected CR events [25], we estimate 15717147's shower energy to be $E = 0.56^{0.3}_{-0.2} \times 10^{18}$ eV, assuming the shower was initiated close to the event's projected position on the ice sheet. For a shower initiated at a height of 4 km above the ice, the energy is reduced by about 30% to $E = 0.40$ EeV.

In addition to the targeted search for UHECR events, we performed two completely independent optimized multivariate blind analyses of all events, favoring impulsive, highly linearly polarized events, without consideration of correlation to any UHECR waveform template [26]. In both of these analyses, all events must be uncorrelated spatially and temporally with human activity and with other detected events, and event 15717147 passed in both cases. These two analyses confirm that event 15717147 is unique, impulsive, and isolated, even when not selected by its UHECR-related properties. The *a posteriori* background estimates for both 15717147 and for the similar anomalous event seen in ANITA-I [6] are at the $\gtrsim 3\sigma$ level.

For detected radio impulses, the large fields of view for the quad-ridged horns used in ANITA allow signals from up to 15 antennas, drawn from up to five azimuthal sectors of the payload, to be coherently combined. Pulse-phase interferometry between these antennas then yields a map of the arrival direction of the radio impulse to typical precisions of 0.25°, 0.65° in elevation and azimuth, respectively [27]. Figure 4 (top) shows the resulting false-color map for event 15717147 in coordinates local to the payload, scaled by the signal-to-noise ratio of the map. Elevation is with respect to the payload horizontal,
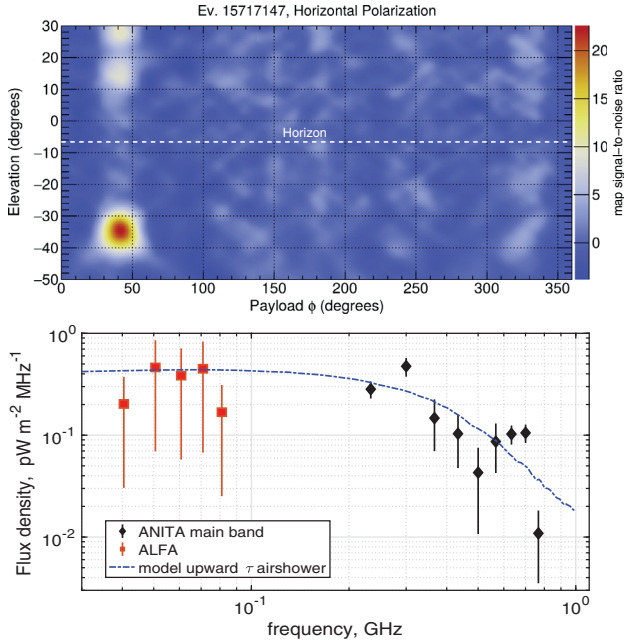
FIG. 4. Top: Interferometric map of the arrival direction of the anomalous CR event 15717147. Bottom: ANITA combined amplitude spectral density for the event, from 40–800 MHz, including data from the ANITA Low Frequency Antenna (ALFA). A simulated upward-propagating extended air shower spectral-density curve is overlain.

and the azimuthal angle ϕ is with respect to the payload heading at the event arrival time. Mapping is done for 360° in ϕ to verify that the mapping solution is unique. Weak sidelobes at 15–25° above the horizon are rejected at very high significance.

ANITA-III flew a separate low-frequency HPOL antenna, the ANITA low-frequency antenna (ALFA), covering the frequency band from 40 to 80 MHz. ALFA's goal was to provide radio-spectral overlap of ANITA UHECR measurements with ground-based data which generally favors bands below 100 MHz. Roughly 3/4 of the UHECR event sample reported here were also detected in the ALFA, and, of those detections, the ALFA data for 15717147 were among the events with the highest

signal-to-noise ratio, in this case $\geq 5\sigma$ above the thermal noise. Figure 4(bottom) shows the combined amplitude spectral density for this event, including the ALFA data. The overlain curve gives the simulated spectral density expected from a τ-lepton initiated EAS, with characteristics consistent with this event [28]. While similar spectral density would be expected for a normal UHECR EAS seen in reflection [14,25], these data further strengthen event 15717147's identification as arising from an extensive air shower–like process.

An alternative explanation of the similar ANITA-I event as due to transition radiation (TR) of an Earth-skimming event has also been proposed [29]. In this model, the plane-of-polarization correlation to geomagnetic angles would be coincidental. Since the event observed in ANITA-III is also well correlated to the local geomagnetic angle, coincidental alignment for both appears probable only at the few percent level. In addition, our simulations and existing literature on analogous TR emission from lightning [30,31] indicate the TR pulse shape is a nearly symmetric bipolar pulse in ANITA's geometry. We have tested the waveform for event 15717147 against phase models for the nearly unipolar pulses from UHECR events, and bipolar pulses, and we find that the UHECR-like pulse shape is favored by 3.4σ over bipolar in our data. Combined with the geomagnetic tension, TR is strongly disfavored as a possible explanation for 15717147. This result applies also to other possible explanations involving Askaryan emission from an in-ice shower with an unusual geometry, since bipolar pulses are also produced in such events. In addition, Askaryan emission has an amplitude spectrum that rises linearly with frequency in the ALFA band, and should produce signals a factor of 4 lower than what is observed at ~ 50 MHz, in clear tension with Fig. 4(bottom).

Table I gives measured and estimated parameters for both of the anomalous CR events, with sky coordinates derived from the arrival direction of the radio impulses.

In our report of the ANITA-I anomalous CR event, we considered the hypothesis that such events could arise through decay of emerging τ leptons generated by ν_τ

TABLE I. ANITA-I,-III anomalous upward air showers.

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[a]	−82.6559, 17.2842	−81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[b]	282.14064, +20.33043	50.78203, +38.65498
E_{shower}[c]	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[a]Latitude, Longitude of the estimated ground position of the event.
[b]Sky coordinates projected from event arrival angles at ANITA.
[c]For upward shower initiation at or near ice surface.

interactions beneath the ice surface. However, the interpretation of these events as τ-lepton decay-driven extended air showers, arising from a diffuse flux of cosmic ν_τ, faces the difficult challenge that the chord lengths through the Earth are such that the SM neutrino cross section [32], even including the effect of ν_τ regeneration [33], will attenuate the flux by a factor of 10^{-5} [28,34].

Assuming the rf source direction as a proxy for the direction of the parent event, 15717147 emerged from the ice with a zenith angle of $\sim 55.5°$, implying a chord distance through the Earth of ~ 7000 km, or 3×10^4 km water equivalent, a total of 18 SM interaction lengths at 1 EeV. For the τ-decay hypothesis, the implied SM Earth-attenuation of the parent neutrino flux is extreme. Even with combined effects of ν_τ regeneration, and significant suppression of the SM neutrino cross section above $\sim 10^{18}$ eV, an alternative model, such as a strong transient flux from a source with compact angular extent, is required to avoid exceeding current bounds on diffuse, isotropic neutrino fluxes.

Suppression of the cross section may occur even within the SM for the extremely low values of the Bjorken-x parameter that obtain at ultrahigh energies. For example, Ref. [35] shows examples where higher-than-expected gluon saturation at $x < 10^{-6}$ causes the UHE deep-inelastic neutrino cross section to saturate at 10^{18} eV, remaining essentially constant above that energy. This yields a factor of 3–4 suppression compared to the SM at 10^{19} eV, approaching an order of magnitude at 10^{20} eV. More recent studies show similar types of suppression are possible, giving factors of 2–3 at 10^{18-19} eV [36,37]. Such SM-motivated scenarios would certainly decrease the exponential attenuation for the Earth-crossing neutrinos relevant to our case, but unless the suppression is an order of magnitude or more, a large transient point-source flux is likely still required. Thus we consider also a search for potential candidate transients that may be associated with this event.

If event 15717147 is a τ-lepton-initiated EAS, the angular error relative to the parent neutrino direction is $\sim 1.5°$, arising from both the width of the emission cone [25], and the intrinsic statistical errors in our estimate of the arrival direction of the rf signal. To investigate this hypothesis further, we point back along the apparent arrival direction, giving sky coordinates shown in Table I. With these parameters, we search existing catalogs for associations with two transient source types for which source confusion is not excessive: gamma-ray burst (GRB) sources, and supernovae. GRBs have been considered as possible UHE neutrino sources for many years, although there are no detections to date. Supernovae (SNE) have also been proposed as UHE sources in a variety of scenarios, both in core-collapse SNE, and more recently even in type Ia SNE, which are believed to originate in the ignition of a white dwarf (WD) progenitor. In the latter case, tidal ignition of a WD by interaction with an intermediate-mass

black hole has been proposed as a potential source of UHECRs [38–40].

In our search, no concurrent GRBs are observed, and one Blazar association is found, with J0322+3948, but is not statistically significant. A SN candidate is found to be associated with possible significance: SN 2014dz, a nearby type Ia SN at $z = 0.017$, is within $1.19°$, well within our expected angular uncertainty on the sky. This relatively bright SN was discovered ~ 7 days before maximum, on 2014-12-20.146 [41]. Our event time follows the initial discovery by just over five hours. Using cataloged SNE discoveries during our flight, and a Bayesian estimator [16], we find the *a posteriori* probability of a chance association with any confirmed SN, at any redshift, within the estimated likely time period of detectability for this SN, is $P \simeq 3.4 \times 10^{-3}$, or 2.7σ.

If SN 2014dz is the source of the putative neutrino candidate, the implied peak isotropic neutrino luminosity must likely far exceed the estimated bolometric luminosity of $L_B = 4.4 \times 10^{42}$ ergs s^{-1}. The lower limit comes already from assuming a much lower cross section than the SM. Alternatively, a beaming hypothesis would significantly relax these constraints.

Both the IceCube [42] and Auger observatories are sensitive to τ leptons, IceCube through events transiting the detector, or via $\tau-$ decay within the detector, and Auger via Earth-skimming $\tau-$ decay-initiated air showers within a few degrees of the horizon [43]. In this case, the declination for IceCube implies an additional ~ 4300 km water equivalent column density, but if the SM cross section is suppressed, the ~ 1 km^2 geometric area of IceCube is still comparable to ANITA's effective point-source geometric area of ~ 4 km^2 at this arrival angle. Auger has potentially a much larger effective point-source area, but only limited exposure around the time of our event. However if the transient flux was as large as it appears, coincident detections in archival data may be possible.

A search of the projected position given by the similar anomalous event from ANITA-I in 2006 yielded no SNE or any other significant association, but the sky position for this event is within $\sim 10°$ from the galactic plane, and thus extinction leads to low SNE detection efficiency for this region of the sky.

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