Characteristics of Four Upward-Pointing Cosmic-Ray-like Events Observed with ANITA

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We report on four radio-detected cosmic-ray (CR) or CR-like events observed with the Antarctic Impulsive Transient Antenna (ANITA), a NASA-sponsored long-duration balloon payload. Two of the four were previously identified as stratospheric CR air showers during the ANITA-I flight. A third stratospheric CR was detected during the ANITA-II flight. Here, we report on characteristics of these three unusual CR events, which develop nearly horizontally, 20–30 km above the surface of Earth. In addition, we report on a fourth steeply upward-pointing ANITA-I CR-like radio event which has characteristics consistent with a primary that emerged from the surface of the ice. This suggests a possible τ-lepton decay as the origin of this event, but such an interpretation would require significant suppression of the standard model τ-neutrino cross section.

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We have previously reported the observation of ultra-high-energy (UHE) cosmic-ray (CR) air showers detected from suborbital altitudes with the Antarctic Impulsive Transient Antenna (ANITA) balloon payload [1] during our first flight in 2007 [2]. The initial blind neutrino-search analysis that led to their identification in the data found 16 events in a signal box with an expected background of 1.6 events. Three of these 16 events were deemed background: two of unknown origin and one a likely thermal noise fluctuation with no apparent signal content. The remaining 13 events were consistent with geomagnetically induced CR radio pulses seen in reflection off the Antarctic ice surface. Three additional CRs were also found in cross-correlation analysis after the unblinding, including two events from directions above the geometric horizon but below the horizontal. These stratospheric air showers represent a class of CR which has not been previously observed.

ANITA [3] makes precise horizontal (Hpol) and vertical (Vpol) polarization measurements of each detected impulse, using custom dual-polarized quad-ridged horn antennas. For the CR events, their nearly horizontal planes

TABLE I. Expected parameters of the three above-horizon CR events.

Event number	Flight	Index	Latitude	Longitude[a]	Angle	D_{1200}[b]	$D_{X\max}$	D_{300}	D_{100}	$H_{X_{\max}}$
5 152 386	I	A	80.2S	49.0W	$-4.25 \pm 0.25°$	$622(+88, -100)$	694 ± 80	780 ± 77	860 ± 70	22.0 ± 1.0
7 122 397	I	B	82.405S	12.5E	$-3.4 \pm 0.32°$	$331(+125, -200)$	$444(+100, -120)$	570 ± 80	667 ± 70	24.2 ± 2.2
21 684 774	II	C	83.24S	0.87E	$-2.3 \pm 0.3°$	$-83.5(+9, -6)$	$-17(+189, -75)$	285 ± 85	416 ± 70	29.9 ± 1.3

[a] Latitude and longitude of the estimated location of shower maximum $X_{\max}$, or for event C, payload location.
[b] Distances from payload, in km, to location of indicated shower slant depth in g/cm^2.

of polarization correlated closely with Lorentz-force components of the predominantly vertical Antarctic geomagnetic field, once Fresnel coefficients for reflection from the ice surface were accounted for. The above-horizon CR events had opposite polarity compared to the reflected events, consistent with a lack of inversion by reflection, and also had geomagnetically correlated planes of polarization. In addition to these two above-horizon events observed in ANITA-I, an additional event of the same type was observed in the 2009 ANITA-II flight, selected according to its high correlation to CR waveform templates. ANITA-II, which was optimized for in-ice neutrino detection [4], did not have a dedicated CR trigger but still detected a small number of CR impulses that had sufficient signal strength. Further details of the two flights are given in Ref. [5].

Motivated by recent results in which searches for upward-directed or Earth-skimming CR air showers have been used to constrain the flux of τ lepton decays arising from UHE ν_τ [6–8], we have performed more detailed evaluation of the properties of these apparently upcoming radio-detected CRs. The three stratospheric events appear consistent with our expectations for ANITA's acceptance to the known CR flux at energies above 10^{18} eV. In reviewing the other putative background events that passed our blind analysis cuts, we found that one of these was dominated by Hpol content, consistent with the geomagnetic parameters of a CR. It arrived at the payload from a direction of 27.4° below the horizontal, which was a fairly typical angle for the reflected CR events. Yet it did not appear to correlate well with the *reflected* CR signal shape and was thus rejected as background at the time [2]. In reevaluating this event, we realized that the polarity and plane of polarization are consistent with an air shower seen directly, without the reflection phase inversion. However, its steep upward-pointing angle poses clear problems for interpretation. In this report, we analyze characteristics of all four of these unusual upward-directed events seen by ANITA, with specific focus on what relation, if any, the previously excluded event may have with τ-lepton-initiated air showers.

Table I shows characteristics of the three stratospheric events. Angles of arrival relative to the payload horizontal and their standard errors are determined through pulse-phase interferometric mapping [9]. Distances to various integrated atmospheric column depths X, including the approximate depth of shower maximum $X_{\max}$, assuming a shower energy of $\sim 10^{18}$ eV, are given along the track, based on a standard atmosphere model for Antarctica, and with uncertainties primarily dominated by the angle-of-arrival uncertainty. The geodetic positions in each case are given according to the estimated location of $X_{\max}$.

Figure 1 shows the field-strength waveforms for all of the events, derived from coherent beam forming [9], with the instrumental response then deconvolved. Both Hpol and Vpol are plotted. The Hpol polarity of each of these events, checked independently by two quantitative methods, is phase reversed with respect to the other 14 UHE CR events which were inverted by reflection from the ice surface [1]. For CRs, Vpol polarity and magnitude depends on components of the geomagnetic field in the locale of the event, as we will quantify later.

The three events at shallow elevation angles, which correlate closely in pulse shape to our other sample of radio-detected CRs, develop, and propagate in the stratosphere, under very rarified densities. Their overall length is greatly magnified compared to showers observed by ground arrays. The lowest of the three events has a likely first interaction point well beyond the geometric horizon

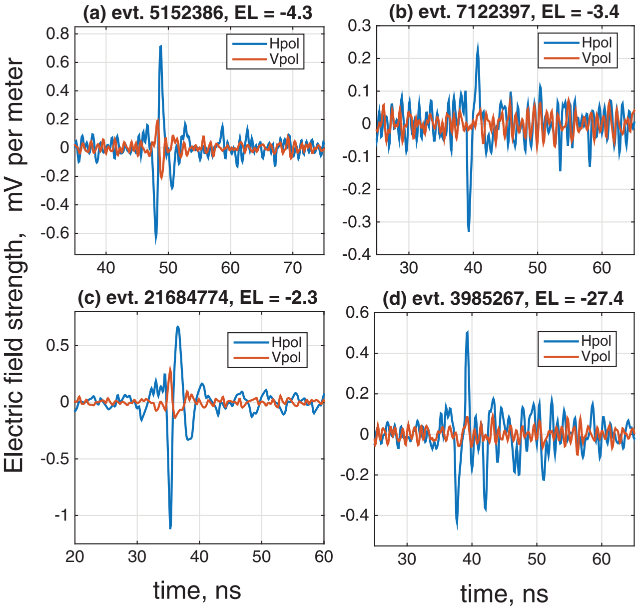

FIG. 1. Waveforms for the four events described here. Events are indexed here and in the text by the letters A, B, C, and D.

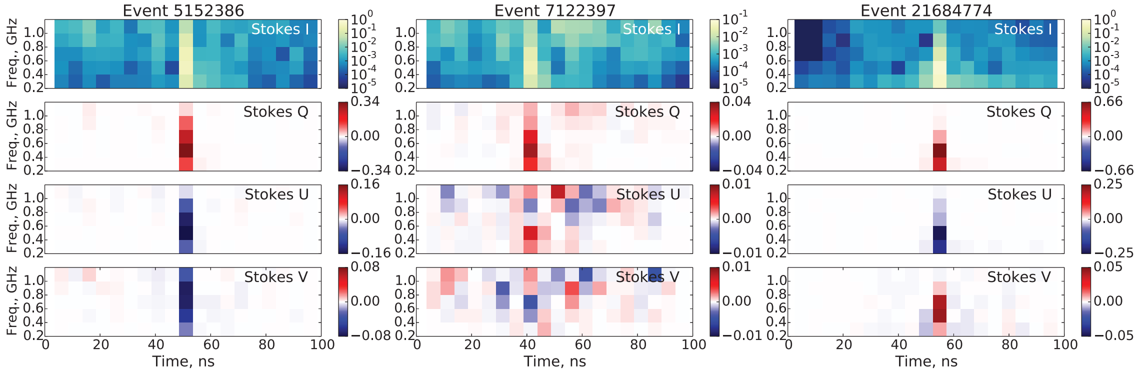

FIG. 2. Stokes parameters for the three above-horizon events in the sample considered here.

and will have largely dissipated in the vicinity of the geometric horizon at $\sim$650 km. The higher two events are at least 200 km and possibly more than 600 km in length, in both cases passing by the ANITA payload before they have dissipated. In the highest event, which develops above 30 km, the shower was near its maximum development when it passed by ANITA. Geometric estimates of ANITA's expected rate of CRs at these angles, using the acceptance determined by the reflected CRs [10], indicates that the number of detected events is consistent with the known CR spectrum at EeV energies.

To characterize these events more fully, we estimate their Stokes parameters. Figure 2 shows I, Q, U, V in a spectrotemporal decomposition for these three events. In all cases, the linear polarization components associated with Q and U are clearly evident. In addition, in the two stronger events, there is up to 25% Stokes V content, indicating circular polarization (CP) present in the signal, well above the $\leq 3\%$ residual instrumental polarization effects for our data. For all of the events, the total polarized fraction is 100% within statistical errors due to thermal noise. CP in radio signals from CRs at the few percent level has been hypothesized to arise from interference between the primary signal generation from geomagnetic effects [11,12] and the secondary signal from the Askaryan effect [13], but there is no currently accepted model to predict the resulting CP content for our signals.

The waveform in Fig. 1 for the remaining event D shows a strong Hpol and a correlated Vpol signal. The primary pulse correlates well with both the above-horizon signals and the inversion of the 14 reflected CR signals. There is also an excess of noise evident in the trailing part of the signal, similar to what is observed in several of the reflected CRs [2], although in this case it appears more persistent and larger in amplitude. In Fig. 3, we show the spectrotemporal plot of Stokes parameters for this event, with clear detections of Q, U, and V, indicating both a linear and CP component; the CP fraction is $\sim$10% of the total polarization.

Table II shows parameters for event D under the hypothesis that it is radio emission from a CR air shower, seen either in reflection from the ice surface or from a direct air shower starting along the track from the surface to the payload, although for the former case the polarity is inconsistent. For the latter case, the only standard model (SM) physics origin we know of for up-going air showers is from the interactions or decay of a secondary lepton from a neutrino interaction; however, at these angles, the chord distance through Earth most likely excludes neutrinos of the energies that ANITA is likely to detect in such a process.

For a cosmic-ray air shower, the Lorentz force on the relativistic electron-positron pairs yields a plane of acceleration in the local shower frame given by $\sin\Psi = \hat{v}\times\hat{B}$, where $\hat{v}$ is a unit vector giving the shower direction and $\hat{B}$ the geomagnetic field direction. The resulting radiation Poynting vector, arising primarily from the region near shower $X_{\max}$, can then be extrapolated to the payload location for each event to determine the predicted field-strength ratio for Vpol to Hpol. Residual nonvertical components of the Antarctic geomagnetic fields will result in small but correlated Vpol components for CR events; anthropogenic or other backgrounds should have no correlation to geomagnetic reference planes. Figure 4 shows results of this analysis for the four events considered here. Errors on the predicted values arise primarily from the combined uncertainties of the Hpol field

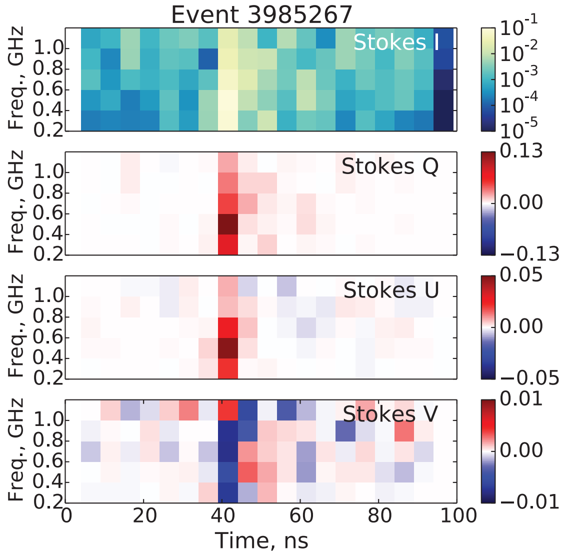

FIG. 3. Stokes parameters for event 3 985 267.

TABLE II. Parameters of event D (flight I) of unknown origin, for both the direct and reflected signal hypotheses.

Hypothesis	Latitude	Longitude[a]	Angle	D_{1200}	$D_{X\,\max}$	$H_{X\,\max}$	D_{300}	D_{100}	$D_{H\,\min}$	$H_{\min}$
Downward CR, reflected	83.16S	18.9E	−27.4 ± 0.3°	84.9	92.2	8.65	105.4	120.3	73.1 ± 0.8	2.59
Upward, direct from ice surface	82.86S	18.15E	−27.4 ± 0.3°	50.7	62.9	7.0	69.4	72.0	73.1 ± 0.8	2.59
Upward, start 5 km above ice	82.56S	17.4E	−27.4 ± 0.3°	[b]	30.6	22.2	54	61	63.1 ± 0.8	7.59

[a] Latitude and longitude of the estimated location of shower maximum $X_{\max}$.

[b] This shower exits the atmosphere at about 800 gm cm^{-2} column depth.

strength and the amplitude calibration between Vpol and Hpol. Measurement errors are dominated by the thermal noise floor. The stratospheric events are all consistent within errors with geomagnetic correlation, as is the case for event D, when evaluated for the geomagnetic parameters of an upward-coming direct event. If the observed polarity of event D were inverted compared to what was observed, it could be marginally consistent with a reflected CR (at the 2.5σ level). However, the statistical chance of a misidentification of the polarity is negligible, since the coherently beam-formed signal-to-noise ratio for the field strength of this event is 16∶1 for Hpol and 4∶1 for Vpol. We thus conclude that a reflected CR hypothesis is excluded for this event. We note also that the measured Vpol/Hpol ratio of the largest secondary peak in this event, occurring 4 ns after the primary peak, is consistent geomagnetically with the first peak, suggesting a similar physical origin for these two components.

The original blind analysis that selected the ANITA-I CR events [1] required only that the events show phase coherence not present in thermal noise fluctuations and that their reconstructed position be isolated both temporally and spatially from all other events. None of the original selection involved waveform correlation, correlation to geomagnetic parameters, or estimates of Stokes V content. For each of these independent parameters, we can use the measured distributions for the background to estimate the cumulative fraction that equals or exceeds our observed values. Assuming they are uncorrelated, the product of these individual probabilities provides an *a posteriori* estimate of the probability that the background could produce this event [5].

The fraction of the 80 000 anthropogenic background events that equal or exceed the magnitude of event D's shape correlation coefficient with the previously identified CRs is $p_{\rm wfm} = 0.022$. Anthropogenic events are uncorrelated to the Antarctic geomagnetic field, and the fraction of such events that equal or exceed event D's geomagnetic correlation is $p_{\rm geo} = 0.07$. The fraction of events with instrumental Stokes V magnitude that exceed that of event D is $p_V = 0.05$. We estimate a trials factor of $f_{\rm trial} = 3$ for a small number of additional parameters investigated as potential discriminators and rejected. Combining these factors, the estimated probability is $p_{\rm wfm} \times p_{\rm geo} \times p_V \times f_{\rm trial} = 2.4 \times 10^{-4}$; given the estimated surviving background of 1.6 events, we would expect $N \simeq 4 \times 10^{-4}$ possible anthropogenic events with characteristics like event D in our data sample. Anthropogenic origin for this event is thus rather strongly disfavored by the data.

For these three parameters, we also have measured values for our CR sample. This allows us to form a likelihood ratio, using Bayes' theorem [14], of the CR hypothesis CR to the anthropogenic hypothesis A:

$$\frac{P(CR|E)}{P(A|E)} = \frac{P(CR)}{P(A)} \frac{P(E|CR)}{P(E|A)}, \qquad (1)$$

where E represents the experimental values. Assuming the two hypotheses are *a priori* equally likely $P(CR) = P(A)$, then we can estimate the terms on the right directly from the data. For the CR sample, we find $q_{\rm wfm} = 0.13$, $q_{\rm geo} = 0.93$, and $q_V = 0.38$, where q here indicates the individual probability for event D given the CR distributions of each of the parameters noted above. The resulting likelihood ratio is

$$P(CR|E)/P(A|E) = (q_{\rm wfm} q_{\rm geo} q_V)/(p_{\rm wfm} p_{\rm geo} p_V) \simeq 550,$$

where the trials factor is common to both cases. The data thus strongly favor the CR hypothesis over the anthropogenic hypothesis, although the latter cannot be excluded at high confidence. This conclusion is consistent with the original analysis, which would almost certainly have

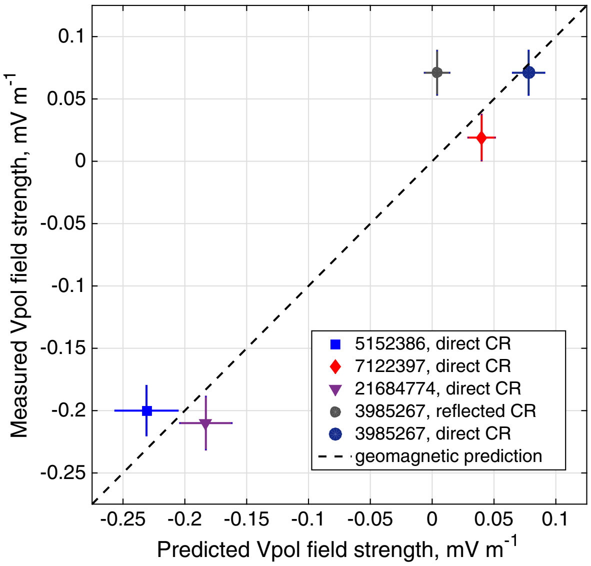

FIG. 4. Geomagnetic correlation of events. The dashed line shows the prediction for pure geomagnetic Lorentz-force-induced emission.

TABLE III. Estimated energy of observed showers; uncertainties are primarily systematic.

Event	(A) 5 152 386	(B) 7 122 397	(C) 21 684 774	(D) 3 985 267
Energy, EeV	9.9 ± 3.0	1.1 ± 0.40	1.2 ± 1.0	0.60 ± 0.40

classified this event as a CR if its polarity had been inverted compared to what was measured.

In Table III, we provide estimates of the energy of each of the air showers considered here, based on the assumption of scaling from simulations of down-going CR [10]. For event D, we consider only the upcoming hypothesis. The uncertainties in each case arise primarily from the lack of precision in the $X_{\max}$ location and related systematic effects. More precise estimates will require detailed simulations that are beyond our scope. For event D, a τ decay origin for the shower still leaves large uncertainty in the location of the decay along the track; indeed, a τ decay higher than about 6 km above the surface leads to a shower that can exit the atmosphere before it even reaches shower maximum.

However, the hypothesis of a τ decay poses difficult problems of interpretation for the parent ν_τ. The minimum emergence angle possible given our angular errors and the uncertainty of where we are on the $\sim 1°$ emission cone is 25.4° [5], with a corresponding chord through Earth of 5450 km, about 20 000 km water equivalent for Earth's density profile. At 1 EeV, the SM neutrino interaction length is of order 1600 km water equivalent and the implied attenuation coefficient is $\sim 4 \times 10^{-6}$, effectively excluding a neutrino origin for this event [5]. Regeneration of ν_τ [15] in Earth can effectively reduce this coefficient by factors of order 2–5 in some cases, but not enough to change this conclusion. Indeed we find that, for SM cross sections, ANITA's geometric acceptance to this type of event should lead to more events observed closer to the horizon, which are not seen. However, SM uncertainties can in some scenarios lead to suppression of the ν cross section at these energies [16], an important effect since it enters through the exponent of the attenuation. Initial estimates indicate that a cross section suppression factor of $\sim$3–5 is required to make this event a plausible ν_τ candidate. This level of suppression would require revision of many current UHE neutrino limits.

We note that the ice depth at the location of this event is 3–4 km; energy loss of a τ lepton in ice is $\sim 1/3$ of that in crustal rock, increasing the probability of survival to decay above the ice surface. This effect can lead to an order-of-magnitude more acceptance for such air showers over ice or water compared to surface land [17]. Also, the τ lepton may itself initiate a shower in the subsurface ice at these high energies which may emerge with the τ and induce an early air shower; this shower's radio emission would be delayed relative to the higher-altitude shower produced by the τ decay. Such a scenario could lead to the correlated trailing noise observed within ≤ 10 ns of the primary peak in the waveform of this event, as it is consistent with refractive atmospheric delay if this portion of the signal originated near the surface of the ice.

Current or future data may be able to confirm or falsify whether neutrino interactions are the origin of this event. To optimize detection for in-ice neutrino events, ANITA-II had a trigger design with low efficiency for CR-like events [4]. For ANITA-III's flight completed last year, the trigger for CR events was reinstated, and data analysis is ongoing. ANITA-IV is scheduled to fly later this year.

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