MURCHISON WIDEFIELD ARRAY LIMITS ON RADIO EMISSION FROM ANTARES NEUTRINO EVENTS

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ABSTRACT

We present a search, using the Murchison Widefield Array (MWA), for electromagnetic counterparts to two candidate high energy neutrino events detected by the ANTARES neutrino telescope in 2013 November and 2014 March. These events were selected by ANTARES because they are consistent, within 0.4, with the locations of galaxies within 20 Mpc of Earth. Using MWA archival data at frequencies between 118 and 182 MHz, taken ∼ 20 days prior to, at the same time as, and up to a year after the neutrino triggers, we look for transient or strongly variable radio sources consistent with the neutrino positions. No such counterparts are detected, and we set a 0.4 limit for low-frequency radio emission of ∼ 10−1 erg s−1 for progenitors at 20 Mpc. If the neutrino sources are instead not in nearby galaxies, but originate in binary neutron star coalescences, our limits place the progenitors at z > 0.2. While it is possible, due to the high background from atmospheric neutrinos, that neither event is astrophysical, the MWA observations are nevertheless among the first to follow up neutrino candidates in the radio, and illustrate the promise of wide-field instruments like MWA to detect electromagnetic counterparts to such events.

Subject headings: radio continuum; general — neutrinos

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1. INTRODUCTION

Neutrinos are believed to be emitted by a range of astrophysical sources (Chiarusi & Spurio 2010; Anchordoqui & Montaruli 2010), including transient sources such as gamma-ray bursts (GRBs), core-collapse supernovae (CCSNe), active galactic nuclei (AGNs), or microquasars. Neutrinos provide a powerful probe of high-energy astrophysical environments, because they are unaffected by magnetic fields, and are extremely unlikely to be absorbed by material between the source and observer. These same properties make them very challenging to detect, even by the largest of the current generation of neutrino observatories, and contaminating background signals are high. However, if their directions can be localized, they have the potential to point directly back to the astrophysical accelerators in which they are created.

Even so, typical positional uncertainties from neutrino telescopes are large enough to encompass many potential electromagnetic (EM) counterparts. A solution to dramatically decrease association ambiguity is to search for transient EM emission that is spatially and temporally consistent with neutrino events. However, aside from neutrinos from the Sun, the only astronomical source so far associated with a neutrino detection (in the tens of MeV energy range) is SN 1987A (Pagliaroli et al. 2009; Bionta et al. 1987; Hirata et al. 1987; Alexeyev et al. 1988) — although recently Kadler et al. (2016) reported a blazar outburst coincident with a PeV-energy neutrino event. Timely multi-wavelength follow-up of neutrino candidates is key in order to attempt to identify the progenitors of astrophysical neutrinos.

The two most sensitive neutrino telescopes currently operating are ANTARES (Ageron et al. 2011) and IceCube (Achterberg et al. 2006). Both search for Cherenkov radiation from secondary particles produced from cosmic neutrinos with energies > 100 GeV. For IceCube (IceCube Collaboration 2013), located at the South Pole, neutrinos from the southern sky are observed as downward-going. Below a PeV, these neutrinos are selected with a vetoing technique that favors the detection of showering events, for which the detector has an angular resolution of only $10^{-15}$. ANTARES, located 40 km off the southern coast of France in the Mediterranean Sea, views the southern sky via upward-going neutrino-induced muon tracks, with a characteristic resolution (50% error circle) of 0.5 (Adrián-Martínez et al. 2014). The detector produces the best limits on neutrino emissions for point-like objects in most of this southern sky region, and hence EM follow-up efforts are concentrated there. A dedicated alert system, TAToO (Ageron et al. 2012), is triggered when a candidate special neutrino event is detected: a single high-energy neutrino; a neutrino in the direction of a gamma-ray burst; an unusual flux of down-going neutrino-induced muon tracks, with a characteristic resolution (50% error circle) of 0.5. For ANTARES, more than 60 neutrino triggers from ANTARES from mid 2013 to mid 2015. Such triggers have different source and observer. These same properties make them very challenging to detect, even by the largest of the current generation of neutrino observatories, and contaminating background signals are high. However, if their directions can be localized, they have the potential to point directly back to the astrophysical accelerators in which they are created.

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The Murchison Widefield Array (MWA), situated in Western Australia, is the Square Kilometre Array precursor at low (80–300 MHz) radio frequencies (Lonsdale et al. 2009; Tingay et al. 2013). The MWA is often used to undertake surveys, for a range of science goals including dedicated (e.g., Bell et al. 2014; Murphy et al. 2015) and commensal (e.g., Rowlinson et al. 2015; Tingay et al. 2015) transient searches, but it has also been used for triggered follow-up of transients at other wavelengths (e.g., Kaplan et al. 2015). Its huge field of view (700 square degrees at 150 MHz) also means that archival observations have a much larger chance, compared to most other radio telescopes, of serendipitously covering an event of interest. This capability is particularly valuable for follow-up of neutrino or gravitational wave (Singer et al. 2015) candidates, which have rather large position uncertainties.

We obtained MWA archival data for both ANTARES triggers, from periods before (Section 3.2) and at the time of (Section 3.1) the trigger, in a search for prompt emission. We also searched for data over a longer range of time to look for late-time emission (Section 3.3).

Flagged CASA (McMullin et al. 2007) measurement sets were produced using the MWA preprocessing pipeline COTTER (Offringa et al. 2015). These were then processed by our custom imaging pipeline, which used WSICLEAN (Offringa et al. 2014) with 40,000 CLEAN iterations to produce XX and YY polarization images with 3072 × 3072 0.9 pixels. The images were amplitude and phase self-calibrated, and primary beam corrected to produce Stokes I images which formed the basis for our analysis. Catalogs were generated using Aegaean (Hancock et al. 2012) and cross-matched across snapshots.

3.1. Search for Prompt Emission

For each of the two triggers, we retrieved 34 MWA datasets, in addition to observations of nearby bright radio calibrators (Pic A for ANT 131121A and Hyd A for ANT 140323A). Exposure times were 112 s, and snapshots were taken approximately every 2 min, from ∼10 min before the neutrino trigger to 1 hr after (sufficiently long to probe dispersion measures > 10^4 pc cm^-3). For ANT 131121A, the central frequency for each observation was 154.255 MHz, and the bandwidth was 30.72 MHz, divided into 768 channels of 40 kHz. ANT 140323A had the same bandwidth and channels, but the central frequency was 182.415 MHz. The MWA synthesized beam is ∼2′ × 2′ at 154 MHz.

One of the 34 snapshots for ANT 131121A failed to image adequately and was discarded. Comparison by eye of the remaining snapshot images for each trigger showed no obvious transients to be present in or near the ANTARES 90% error circles, which are 1° in radius (Adrián-Martínez et al. 2014). Additionally, no transients (sources ≥5 times brighter than the background fluctuations) were present in catalogs corresponding to a single snapshot within the ANTARES error circles.

We extracted square image cutouts 5° on a side centered on the trigger positions, and combined these, taking the median value at each pixel position, to create a deep image for each trigger (center panels of Figure 1). We also measured the RMS flux density in the object-subtracted background sky, σ_{sky} (which corresponds to the sensitivity), in the 5° × 5° regions centered on each trigger. The flux density for the faintest detectable source was set at 4σ_{sky}.

The mean σ_{sky} of the 33 ANT 131121A prompt snapshot images was 48 mJy beam^{-1}, and the standard deviation of σ_{sky} for these images was 4 mJy beam^{-1}. The 34 ANT 140323A prompt snapshots had σ_{sky} = 87 ± 7 mJy beam^{-1}. For ANT 131121A, σ_{sky} for the deep image made from the 33 snapshots should naively correspond to 48/√33 = 8 mJy beam^{-1}. After the snapshots have been median combined (i.e. the median at each pixel is used), however, the measured σ_{sky} is somewhat higher (18 mJy beam^{-1}) than the naive expectation, due to the presence of sidelobes and confused sources (Wayth et al. 2015). Similarly, for ANT 140323A we obtained 47 mJy beam^{-1} for the deep median-combined image. The difference in sensitivity between the two fields is partly because of the difference in frequencies, and partly because ANT 140323A is closer to the edge of the MWA primary beam than ANT 131121A, resulting in higher σ_{sky}.

3.2. Pre-trigger Comparison Images

We also retrieved archival MWA data from ∼20 days prior to each trigger. For ANT 131121A we obtained 30 observations at 154 MHz from UT 2013 Nov 1. For ANT 140323A we obtained 31 observations at 182 MHz from UT 2014 Mar 2. These were analyzed in the same manner as described above. Deep images made from combining the ∼1 hr of observations for each trigger are shown in the left panels of Figure 1. Comparison of the pre-trigger and prompt deep images by eye again showed no obvious transients.

We used the matched snapshot catalogs (independently for the pre-trigger and prompt datasets) to measure the mean (S) and standard deviation (σ_S) of the flux densities of radio sources detected in our data. For all sources detected in at least 10 of the ∼30 snapshots, we computed variability statistics (reduced chi-squared, χ_r^2, and fractional modu-
Figure 1. $5^\circ \times 5^\circ$ cutouts from median-combined deep images on each of the two triggers (top: ANT 131121A; bottom: ANT 140323A). From left to right, images were taken $\sim 20$ days prior to, at the time of, and over the course of $\sim 1$ yr after the trigger time (Table 2). Some faint image artifacts are visible, particularly in the top panels around the bright source Fornax A. In the bottom panels, enhanced noise is visible towards the bottom due to the effects of the fall-off in sensitivity towards the edge of the primary beam. The greyscale runs from 0 to 1 Jy beam$^{-1}$. The 90% ANTARES error circles (radius $1^\circ$) are shown.

The majority of points in our variability plots occupy a contiguous region of parameter space, with brighter sources tending to be detected in more snapshots, and having higher $\chi^2_{\psi}$, as would be expected given improved signal to noise for these sources. Very few well-detected sources (those seen in $\sim 30$ snapshots) exhibit $\sigma_S/S \gtrsim 50\%$, with the exception of the largest (i.e. brightest) two points in the ANT 131121A prompt plot, which have $\sigma_S/S = 0.59$ and 0.55 respectively. Both have $\chi^2_{\psi} \approx 10$, suggesting that they are indeed strongly variable. However, both are coincident with the lobes of Fornax A, and while variability of an AGN core is possible on short timescales, variability of extended lobe emission is not. We conclude therefore that the apparent variability here is caused by the difficulty of fitting point source models to extended emission. Variations in sensitivity and image quality result in different fits at each epoch, which is also why these sources do not appear in the same position in the top left panel of Figure 2. In any case, Fornax A is too far from the trigger position, given the ANTARES positional uncertainties, to be the neutrino source (likelihood of association $\sim 5 \times 10^{-4}$).

The plots for ANT 140323A show fewer sources, due to the poorer sensitivity associated with the location of this candidate towards the edge of the primary beam. Nevertheless there are no well-detected sources that appear as outliers in the prompt data and not in the pre-trigger data. We conclude, therefore, that our observations did not convincingly detect any strong AGN flares associated with the neutrino triggers.

3.3. Search for Late-Time Emission

The MWA observing strategy, in particular changes in programs from one season to the next, somewhat restricts our ability to obtain a long-timescale follow-up of any given position of interest by simply searching the archive (as opposed to undertaking a dedicated follow-up campaign). Nevertheless, we were able to retrieve observations for both triggers that can be used to constrain late-time emission. We searched the archive for observations evenly distributed in log(time): 1, 2, 4, ..., 8192 hr after the trigger. In most cases we were able to find data close in time to the desired epoch (Table 2). When no suitable data were present in the archive that were closer in log(time) to a given epoch than to the previous or next epoch, that epoch was skipped.

Images were produced in the same manner as described above. Snapshot image sensitivity (which can be sensitive to the inclusion of relatively small amounts of poor quality data), $\sigma_{\text{sky}}$, ranged from 49–373 mJy beam$^{-1}$ (Table 2). Once again, we made deep images (right panels of Figure 1) by median-combining snapshots. Since the snapshots were taken over a wide range in time (see Table 2) the median will de-emphasize sources which vary with a characteristic timescale $\ll 1$ yr. These images nevertheless provide good sensitivity to long-timescale transient or variable sources associated with the neutrino.

Once again, neither trigger had an obvious transient counterpart, either in the snapshots, or the deep images.
MWA Follow-up of ANTARES Triggers

4. LIMITS ON PROGENITORS

ANTARES detects \( \sim 2 \) atmospheric neutrinos per day with energies comparable to our two events (\( \gtrsim 1 \) TeV). However, both candidates were generated by the ANTARES directional trigger (Section 2), having positions coincident with galaxies within 20 Mpc. Such coincidences represent \( \sim 2\% \) of the background from atmospheric events (Adrián-Martínez et al. 2015b). If we assume the ANTARES neutrinos are indeed astrophysical, rather than due to terrestrial backgrounds, we can use our data to place some of the first low-frequency radio limits on EM counterparts to neutrino events. If the nearby galaxies are the hosts of the neutrino progenitors, this allows us to place limits on the luminosity of any EM counterpart.

Using 5\( \sigma \) upper limits of 90 to 340 mJy (based on \( \sigma_{\text{sky}} \) for the deep images in Table 2, which ranges from 18 to 68 mJy beam\(^{-1}\)), we obtain \( L_{150\text{MHz}} \lesssim 10^{29} \) erg s\(^{-1}\) Hz\(^{-1}\) (\( \lesssim 10^{29} \) erg s\(^{-1}\)) for progenitors at 20 Mpc. These limits are not strongly constraining of late-time emission from even the most luminous radio supernovae or GRBs at these distances; during the first \( \sim 100 \) days after the event, radio emission at MWA frequencies would be expected to be \( \lesssim 10^{28} \) erg s\(^{-1}\) Hz\(^{-1}\) (Soderberg et al. 2010). Our limits are better (\( \lesssim 10^{27} \) erg s\(^{-1}\) Hz\(^{-1}\)) if ANT 140323A is associated with the Antlia Dwarf at 1.3 Mpc, but this still does not provide a strong constraint on progenitors. In fact, due to synchrotron self-absorption at low radio frequencies, late-time emission tends to be faint in general (e.g. Metzger et al. 2015), further emphasizing the need for rapid response or simultaneous observations to search for brighter prompt radio emission.

For GRBs or CCSNe at distances \( < 20 \) Mpc, we consider whether counterparts should have been seen in the optical observations (Section 2). At 20 Mpc, the optical limit of 18.7 mag corresponds to absolute magnitudes brighter than \( -13 \), sensitive enough to detect all but the faintest (e.g. Pastorello et al. 2007) supernovae, although this does not account for dust obscuration in the host galaxy. We also consider a scenario where the nearby galaxies are chance alignments, and the progenitors are in fact at larger distances. Considering the possibility that the neutrinos might be from binary neutron star coalescences such as those modeled by Pshirkov & Postnov (2010), our upper limits for prompt emission, with their Equation 8 and assuming an efficiency scaling exponent \( \gamma = 0 \), would place such progenitors at distances \( \gtrsim 1 \) Gpc (\( \gtrsim 0.2 \)).

5. OUTLOOK

Although the MWA has excellent capabilities for these kinds of serendipitous searches due to its wide field of view, the use of archival data has limitations. Neither trigger was optimally placed within the MWA field of view: ANT 131121A was \( \sim 8^\circ \) from the pointing center, and ANT 140323A was \( \sim 17^\circ \) away. Particularly in the latter case, the fall-off in primary beam response means that noise in the

![Figure 2](image-url)
Table 2

<table>
<thead>
<tr>
<th>UT date</th>
<th>UT time</th>
<th>Time since trigger (hr)</th>
<th>Frequency (MHz)</th>
<th>( \sigma_{xy} ) (mJy beam(^{-1}))</th>
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</thead>
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<td>18:15:12</td>
<td>-477</td>
<td>154</td>
<td>24</td>
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<td>0</td>
<td>154</td>
<td>18</td>
</tr>
<tr>
<td>2013 Nov 21</td>
<td>16:59:04</td>
<td>2</td>
<td>154</td>
<td>49</td>
</tr>
<tr>
<td>2013 Nov 22</td>
<td>18:36:40</td>
<td>4</td>
<td>154</td>
<td>93</td>
</tr>
<tr>
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<td>14:47:04</td>
<td>24</td>
<td>154</td>
<td>51</td>
</tr>
<tr>
<td>2013 Nov 26</td>
<td>18:16:56</td>
<td>123</td>
<td>154</td>
<td>201</td>
</tr>
<tr>
<td>2013 Dec 3</td>
<td>14:18:56</td>
<td>287</td>
<td>154</td>
<td>50</td>
</tr>
<tr>
<td>2013 Dec 6</td>
<td>15:25:28</td>
<td>360</td>
<td>154</td>
<td>200</td>
</tr>
<tr>
<td>2014 Feb 14</td>
<td>13:00:56</td>
<td>2038</td>
<td>154</td>
<td>337</td>
</tr>
<tr>
<td>2014 Jul 20</td>
<td>22:20:24</td>
<td>5791</td>
<td>154</td>
<td>48</td>
</tr>
<tr>
<td>2014 Oct 28</td>
<td>16:48:24</td>
<td>8185</td>
<td>154</td>
<td>70</td>
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<tr>
<td>Late-time average(a)</td>
<td>…</td>
<td>2 – 8185</td>
<td>118, 154, 182</td>
<td>34</td>
</tr>
<tr>
<td>2014 Mar 2</td>
<td>16:20:16</td>
<td>-503</td>
<td>154</td>
<td>36</td>
</tr>
<tr>
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<td>15:21:12</td>
<td>0</td>
<td>154</td>
<td>47</td>
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<td>2014 Mar 24</td>
<td>12:36:40</td>
<td>21</td>
<td>154</td>
<td>135</td>
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<td>2014 Mar 26</td>
<td>12:28:48</td>
<td>68</td>
<td>154</td>
<td>143</td>
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<td>2014 Apr 3</td>
<td>11:57:20</td>
<td>260</td>
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<td>135</td>
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<td>2014 Apr 13</td>
<td>15:05:44</td>
<td>503</td>
<td>154</td>
<td>178</td>
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<tr>
<td>2014 May 5</td>
<td>10:31:12</td>
<td>1027</td>
<td>154</td>
<td>93</td>
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<tr>
<td>2014 Oct 25</td>
<td>21:34:00</td>
<td>5190</td>
<td>154</td>
<td>373</td>
</tr>
<tr>
<td>2015 Feb 16</td>
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<td>8160</td>
<td>154</td>
<td>68</td>
</tr>
<tr>
<td>Late-time average(a)</td>
<td>…</td>
<td>21 – 8160</td>
<td>154</td>
<td>68</td>
</tr>
</tbody>
</table>

\(a\) Deep images made from median combining snapshot images.

\(b\) Individual late-time snapshot images.

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Pagliaioli, G., Vissani, F., Costantini, M. L., & Ianni, A. 2009, Astroparticle Physics, 31, 163
White, D. J., Daw, E. J., & Dhillon, V. S. 2011, Classical and Quantum Gravity, 28, 085016