Arcminute Microkelvin Imager observations of unmatched Planck ERCSC LFI sources at 15.75 GHz

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ABSTRACT
The Planck Early Release Compact Source Catalogue includes 26 sources with no obvious matches in other radio catalogues (of predominantly extragalactic sources). Here we present observations made with the Arcminute Microkelvin Imager Small Array (AMI SA) at 15.75 GHz of the eight unmatched sources at \( \delta > +10^\circ \). Of the eight, four are detected and are associated with known objects. The other four are not detected with the AMI SA, and are thought to be spurious.

Key words: ISM: individual objects: NGC 7133 – ISM: individual objects: NGC 1333 – ISM: individual objects: Cygnus Loop – planetary nebulae: individual: NGC 40 – ISM: supernova remnants – radio continuum: general.

1 INTRODUCTION
The Planck Early Release Compact Source Catalogue (ERCSC: Planck Collaboration 2011a) consists of compact sources detected at each of the Planck frequency bands, covering a range from 30 to 857 GHz. The Low Frequency Instrument (LFI; 30-, 44- and 70-GHz frequency bands) sources are matched against archival data at lower frequencies both for validation purposes and the construction of spectral energy distributions. 26 sources in the Planck ERCSC are reported as having no plausible match in existing, lower frequency radio catalogues of primarily extragalactic sources. Planck Collaboration (2011b) conclude that the majority of the unmatched sources are either spurious, explained by extended Galactic structures, or have very unusual spectra.

The Arcminute Microkelvin Imager Small Array (AMI SA) is a radio interferometer specifically designed to have good sensitivity to low-surface-brightness, extended features. It operates at 15.75 GHz, relatively close in frequency to the Planck LFI. We therefore decided to observe the eight of the unmatched sources which are visible to the AMI SA, having \( \text{J2000 } \delta > +10^\circ \) (see Table 1), consisting of sources detected at 44 or 70 GHz (none of the unidentified sources detected at 30 GHz was accessible). The full width at half-maximum (FWHM) of the AMI SA primary beam is \( \lesssim 20 \) arcmin, so its field of view is comparable to the Planck beam sizes of \( \lesssim 27 \) and \( \lesssim 13 \) arcmin at 44 and 70 GHz, respectively; the AMI SA is also sensitive to angular scales up to \( \lesssim 10 \) arcmin, so will be able to detect extended objects visible to Planck that may have been resolved out in some surveys.

2 OBSERVATIONS AND DATA REDUCTION
The AMI SA is situated at the Mullard Radio Astronomy Observatory, Cambridge (AMI Consortium: Zwart et al. 2008). It consists of 10 3.7-m-diameter dishes with a baseline range of \( \lesssim 5–20 \) m and observes in the band 12–18 GHz with eight 0.75-GHz bandwidth channels. In practice, the lowest two frequency channels are unused due to a low response in this frequency range and interference from geostationary satellites. The FWHM of the SA synthesized beam (for combined channel maps) is \( \lesssim 2 \) arcmin; figures shown include the synthesized beam, which is an effective measure of the resolution.

*We request that any reference to this paper cites ‘AMI Consortium: Perrott et al. 2012’.
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Table 1. The Planck unidentified sources observed with the AMI SA and the sources used as phase calibrators. Planck source names contain the frequency of detection (i.e. PLCKERC044 indicates a source detected at 44 GHz) and the Galactic coordinates of the source.

| Planck ID | RA (J2000) | δ (J2000) | Phase calibrator |
|-----------|------------|-----------|------------------|
| PLCKERC044 G070.52−08.69 | 20 55 58.6 | +31 46 11 | J2109+3532 |
| PLCKERC044 G105.35+09.85 | 21 42 49.2 | +66 03 11 | J2125+6423 |
| PLCKERC044 G105.43−07.07 | 22 55 58.8 | +51 49 43 | J2322+5057 |
| PLCKERC044 G181.80+56.02 | 10 18 32.5 | +39 39 39 | J1034+3948 |
| PLCKERC070 G053.99−10.45 | 20 08 54.6 | +13 24 23 | J2016+1632 |
| PLCKERC070 G095.46+45.89 | 15 39 06.7 | +61 17 10 | J1551+5806 |
| PLCKERC070 G120.02−09.88 | 00 13 08.2 | +72 32 19 | J0019+7327 |
| PLCKERC070 G158.33−20.53 | 03 29 03.6 | +31 17 21 | J0329+2756 |

Table 2. Assumed τ + Q flux densities of 3C 286, 3C 48 and 3C 147.

| Channel | ν (GHz) | S^3C 286 (Jy) | S^3C 48 (Jy) | S^3C 147 (Jy) |
|---------|---------|---------------|---------------|---------------|
| 3 | 13.88 | 3.74 | 1.89 | 2.72 |
| 4 | 14.63 | 3.60 | 1.78 | 2.58 |
| 5 | 15.38 | 3.47 | 1.68 | 2.45 |
| 6 | 16.13 | 3.35 | 1.60 | 2.34 |
| 7 | 16.88 | 3.24 | 1.52 | 2.23 |
| 8 | 17.63 | 3.14 | 1.45 | 2.13 |

The eight sources listed in Table 1 were observed from 2011 March 21 to 23. Each source was observed twice, for 1 h at a time, at different hour angles in order to improve the uυ-coverage. PLCKERC044 G105.43−07.07 and PLCKERC044 G181.40+56.02 were also re-observed for 6 and 16 h, respectively, on 2011 August 13–14 in order to improve extent and spectral index constraints (see Section 3.2.1).

Data reduction was performed using the local software tool REDUCE, which flags interference, shadowing and hardware errors, applies phase and amplitude calibrations, and Fourier transforms the correlator data to synthesize the frequency channels, before output to disc in uυ FITS format. Flux calibration was performed using short observations of 3C 48, 3C 286 or 3C 147 near the beginning and end of each run. The assumed flux densities for 3C 286 were converted from Very Large Array total-intensity measurements provided by R. Perley (private communication), and are consistent with the Rudy et al. (1987) model of Mars transferred on to absolute scale, using results from the Wilkinson Microwave Anisotropy Probe. The assumed flux densities for 3C 48 and 3C 147 are based on long-term monitoring with the AMI SA using 3C 286 for flux calibration (see Table 2). A correction for changing airmass is also applied using a noise-injection system, the ‘rain gauge’.

Bright, nearby point sources selected from the Very Long Baseline Array Calibrator Survey (Peck & Beasley 1998) were observed during each observation at hourly intervals for phase calibration purposes (see Table 1 for phase calibrators used for the AMI SA observations). The reduced visibility data were imaged using AIPS,1 from combined channel data sets (for channels 3–8 inclusive), with a central frequency of 15.75 GHz. Errors on AMI SA flux density values were estimated by adding in quadrature the rms map noise (σ rms, measured from the CLEANed maps) and the error on flux calibration (including rain-gauge correction) of ≃5 per cent.

3 RESULTS AND DISCUSSION

Maps displayed are not corrected for attenuation due to the primary beam; the flux densities reported have been so corrected. Where spectral indices α are quoted, the convention S ∝ ν ^−α is used, where S is flux density and ν is frequency. Errors quoted are σ S Planck refers to the positional error appropriate to each Planck source, as quoted in the ERCSC.

Data from the following surveys have been used for reference: the VLA Low-Frequency Sky Survey (VLSS; Cohen et al. 2007), the 7C survey (7C; Visser et al. 1995), the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997), the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), the Green Bank 4.85 GHz survey (GB6; Gregory et al. 1996) and the Cosmic Lens All-Sky Survey (CLASS; Myers et al. 2003). The specfind v2.0 catalogue was also used (Vollmer et al. 2010).

3.1 Sources detected and associations with known objects

Four of the sources are detected by the AMI SA and are associated with known optical sources, all of which are in the New General Catalogue (NGC; Dreyer 1888). These are described below and listed in Table 3.

PLCKERC044 G070.52−08.69. An extended source is detected at 121σ rms (see Table 3) in the AMI SA map, with the peak of the emission at 2.6σ Planck from the Planck position. This is associated with NGC 6992, the north-eastern portion of the Cygnus Loop supernova remnant (see e.g. Green 1990). Fig. 1 shows Digitized Sky Survey (DSS) red data overlaid with AMI SA contours. Due to the extent of the source, the AMI SA and Planck data are beyond the scope of this Letter.

PLCKERC044 G105.35+09.85. An extended source is detected at 43σ rms (see Table 3) in the AMI SA map, with the peak of the emission at 2.3σ Planck from the Planck position. This is associated with the reflection nebula NGC 7133. Fig. 2 shows DSS red data overlaid with AMI SA contours. Reflection nebulae are expected to emit at 15.75 GHz and more strongly at 44 GHz due to a combination of free–free, vibrational dust and possibly spinning dust emission (Draine & Lazarian 1998; Castellanos et al. 2011). The AMI SA and Planck measurements are therefore qualitatively consistent in that the spectrum is rising (see Table 3); however, a quantitative analysis would be complicated due to flux loss and is beyond the scope of this paper.

PLCKERC070 G120.02+09.88. A point source is detected at 647σ rms (see Table 3) in the AMI SA map with the peak of the emission at 1.4σ Planck from the Planck position. This is associated with the planetary nebula NGC 40. Fig. 3 shows DSS red data overlaid with AMI SA contours. NGC 40 is a well-studied planetary nebula (see e.g. Leal-Ferreira et al. 2011; Monteiro & Falceta-Gonçalves 2011), which was first identified by Herschel in 1788 (Herschel 1789). Although it is compact to the AMI SA beam, its position on the rim of the supernova remnant CTA 1 (see e.g. Sun et al. 2011) makes constructing a radio spectrum for it difficult because of the extra extended emission which may be measured by single dishes, depending on the background subtraction method used; for a recently compiled spectrum at radio frequencies below 44 GHz, see Sun et al. A search of the Planck catalogue shows probable associations at 100 and 143 GHz also, at 2.2σ Planck and 1.3σ Planck from the AMI SA position, respectively. The measurement at 143 GHz (553 ± 31 mJy) is lower than the 70-GHz (688 ± 135 mJy) and 100-GHz (776 ± 58 mJy) measurements – this may be an

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1 http://aips.nrao.edu/
Table 3. Planck unidentified LFI sources which are detected with the AMI SA, and are associated with known optical sources. These are supernova remnants (SNR), reflection nebulae (RNe) or planetary nebulae (PNe). In each case, the distances to the peaks of the emission detected with the AMI SA and the peak flux densities are given.

| Planck ID           | Planck flux density (mJy) | Planck positional error (arcmin) | AMI SA peak flux density (mJy beam$^{-1}$) | AMI SA σ$_{\text{rms}}$ (μJy beam$^{-1}$) | Distance from Planck position (arcmin) | Optical association | Object type |
|---------------------|---------------------------|---------------------------------|---------------------------------------------|------------------------------------------|--------------------------------------|---------------------|-------------|
| PLCKERC044 G075.52−08.69 | 1769 ± 165               | 1.7                             | 79 ± 4                                      | 560                                      | 4.5                                   | NGC 6992           | SNR         |
| PLCKERC044 G105.35+09.85 | 1342 ± 117               | 1.7                             | 14.1 ± 0.8                                  | 290                                      | 3.9                                   | NGC 7133           | RNe         |
| PLCKERC070 G120.02+09.88 | 688 ± 135                | 0.87                            | 350 ± 18                                    | 540                                      | 1.2                                   | NGC 40             | PNe         |
| PLCKERC070 G158.33−20.53 | 2089 ± 165               | 1.0                             | 7.5 ± 0.6                                   | 410                                      | 1.9                                   | NGC 1333           | RNe         |

*Part of the Cygnus Loop (see e.g. Green 1990).*

3.2 Non-detections

Although some sources were detected near the positions of the remaining four Planck unidentified sources, these were classed as non-detections. Flux detection limits are taken as 5σ$_{\text{rms}}$ as measured from the map, with the exception of PLCKERC070 G095.46+45.89 which is dynamic-range-limited due to the presence of a bright source; in this case, the flux detection limit is taken as the peak flux density of the brightest non-believable feature.

PLCKERC044 G105.43−07.07. Two faint (peak flux density ≤1.0 mJy) point sources are detected in the AMI SA map within 1.9 arcmin (1.0σ$_{\text{Planck}}$) from the Planck position. These are associated with three NVSS point sources with flux densities of 7.4, 8.8 and 8.7 mJy, indicating a falling spectrum inconsistent with the Planck flux density of 1558 ± 231 mJy at 44 GHz.

PLCKERC044 G181.40+56.02. Three faint (peak flux density ≤1.9 mJy) point sources are detected in the AMI SA map within...
There are three possible reasons for the non-detection of these unidentified sources if they are real. For a compact (to the SA beam), non-variable source, non-detection could be due to a rising spectrum between 15.75 GHz and the Planck frequency of detection. A limiting spectral index for this case can be calculated using the AMI SA flux detection limit. For the 44-GHz sources, the calculated spectral indices are found to be non-physical ($<-7$). For the 70-GHz sources, they are $<-3$ which would require extreme thermal dust emission, but the flux densities extrapolated to the higher Planck frequencies using the spectral index limits are well above the Planck flux detection limits at the corresponding frequencies, and these sources are not detected at any other frequencies. The mean SA beam FWHM taken from the observations of the four non-detected sources is $\simeq 165$ arcsec, so it can be concluded that non-variable sources on this scale corresponding to the Planck detections do not exist.

Variability is significant at AMI frequencies, and even more so at Planck frequencies (see e.g. fig. 11 of Planck Collaboration 2011b). Many Planck sources are expected to be blazars, and detections near the flux density limits are more likely to be in a flare state. Richards et al. (2011) monitored the fluxes of 1158 blazars with the Owens Valley Radio Observatory (OVRO) 40-m telescope at 15 GHz, on a biweekly basis for over 3 years. The largest peak-to-trough amplitude ratio found in the sample was $\simeq 43$, with a time-scale of just under a year between the peak and trough. The AMI SA observations were taken between just under 1–2 years after the Planck observations, so the non-detected Planck sources could potentially be blazars detected in a flare state by Planck, while the AMI SA observations were made during a low state.

In the case of the 44-GHz sources, multiplying the AMI SA flux detection limits by 43 still implies extreme spectral indices between 15.75 and 44 GHz of $<-3.6$ and $<-3.8$, respectively. Two of the three 44-GHz receivers are located at the opposite side of the Planck focal plane from the third, which is next to the 30- and 70-GHz receivers, and observe the same point on the sky roughly a week apart in time from the other receivers. It is therefore conceivable that a blazar in a flare state could be observed at 44 GHz but not at the neighbouring frequencies. However, in that case, the effect of averaging between the three 44-GHz receivers could only lower the reported flux, requiring the spectral indices between 15.75 and 44 GHz to be even more extreme. In the case of the 70-GHz sources, multiplying the AMI SA flux detection limits by 43 implies spectral indices between 15.75 and 70 GHz of $<-0.96$ and $<-0.68$, respectively. The 100-GHz receivers are located next to the 70-GHz receivers, and the Planck flux detection limit at 100 GHz is 344 mJy, so in order for these sources not to be detected simultaneously at 100 GHz, the spectra must turn over to have indices $>-2$ between 70 and 100 GHz. Similar spectra are observed (see fig. 5 of Planck Collaboration 2011b), so this possibility cannot be ruled out. It should be noted, however, that blazars with a high variability amplitude are found to be more likely to be gamma-ray-loud (Richards et al. 2011), and none of these sources is matched in the Fermi Large Area Telescope first source catalogue (Abdo et al. 2010).

Alternatively, if a source is extended on scales larger than the SA beam, flux will be ‘resolved out’ due to undersampling of the large spatial scales. All of the sources are indicated in the Planck ERCSC as being compact to the Planck beam and should therefore be of the size of the beam or smaller. An upper limit on the spectral index for each source can be calculated for which a Gaussian source of the same size as the Planck beam would be undetected in the AMI SA beam.
map. For simplicity, the limit is calculated using a circular Gaussian source with FWHM equal to the Planck major axis beam size quoted in the catalogue.

To calculate the flux loss for a Gaussian source with a given FWHM, a simulated source was sampled with the real $uv$-coverage from the observations, then mapped in AIPS to recover a peak flux density. To recover more flux on extended scales, a ‘$uv$-taper’ of 300$\lambda$ was applied. This is a Gaussian weighting function which downweights the longer baselines, with a distance of 300$\lambda$ to the 30 per cent point, where $\lambda$ is the central wavelength of the observation. The peak flux density recovered can be compared with the peak flux required for detection on the $uv$-tapered AMI SA maps. Flux limits and limiting spectral indices are quoted for each source in Table 4. The spectral index limits are not implausible; however, the spectra implied are nearly all very steeply rising, and are upper limits since if the source is smaller than the beam size the ‘true’ spectral index limits will be even more negative.

Each source in the ERCSC is assigned a ‘reliability’ value between 0 and 1, corresponding to the probability that a source lying in a patch of sky with a given sky noise will have an estimated flux density accurate to within 30 per cent (Planck Collaboration 2011a). The reliability values for these undetected sources (see Table 4) are comparable to the lowest reliability value in the entire catalogue, 0.74. Additionally, all of these sources have a ‘CMBSUBTRACT’ flag set to either 2 or 1 in the ERCSC. This means that they are either not detected in the CMB-subtracted maps or are detected with a flux density difference $>30$ per cent compared to the flux density detected on the non-subtracted maps, respectively. In contrast, the unidentified sources that were detected with the AMI SA have reliability values ranging from 0.84 to 0.96, and only two have ‘CMBSUBTRACT’ flags set to 1, while the other two are set to 0. Thus, although the AMI SA observations cannot rule out the possibility that the non-detections are either variable or real, extended sources with rising spectra, it seems more likely that these unidentified sources are spurious.

4 CONCLUSIONS

Of the eight unidentified Planck LFI sources observable with the AMI SA, four are detected at 15.75 GHz and are associated with known objects. The other four are not detected. Calculations of limiting spectral indices show that the undetected sources cannot be non-variable and compact at or below the scale size of the AMI SA beam. The possibility that they are either variable or extended sources with steeply rising spectra between 15.75 and 44 or 70 GHz cannot be ruled out by the AMI SA observations; however, combined with the relatively low Planck reliability values and ‘CMBSUBTRACT’ flags for these sources, it seems likely that they are spurious.

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