



AN OPPORTUNISTIC SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) WITH THE MURCHISON WIDEFIELD ARRAY

S. J. TINGAY^{1,2}, C. TREMBLAY¹, A. WALSH¹, AND R. URQUHART¹

¹ International Centre for Radio Astronomy Research (ICRAR), Curtin University, Bentley, WA 6102, Australia

² Istituto di Radioastronomia, Istituto Nazionale di Astrofisica, I-40129 Bologna, Italy

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ABSTRACT

A spectral line image cube generated from 115 minutes of MWA data that covers a field of view of 400 sq. deg. around the Galactic Center is used to perform the first Search for ExtraTerrestrial Intelligence (SETI) with the Murchison Widefield Array (MWA). Our work constitutes the first modern SETI experiment at low radio frequencies, here between 103 and 133 MHz, paving the way for large-scale searches with the MWA and, in the future, the low-frequency Square Kilometre Array. Limits of a few hundred mJy beam⁻¹ for narrowband emission (10 kHz) are derived from our data, across our 400 sq. deg. field of view. Within this field, 45 exoplanets in 38 planetary systems are known. We extract spectra at the locations of these systems from our image cube to place limits on the presence of narrow line emission from these systems. We then derive minimum isotropic transmitter powers for these exoplanets; a small handful of the closest objects (10 s of pc) yield our best limits of order 10¹⁴ W (Equivalent Isotropic Radiated Power). These limits lie above the highest power directional transmitters near these frequencies currently operational on Earth. A SETI experiment with the MWA covering the full accessible sky and its full frequency range would require approximately one month of observing time. The MWA frequency range, its southern hemisphere location on an extraordinarily radio quiet site, its very large field of view, and its high sensitivity make it a unique facility for SETI.

Key words: instrumentation: interferometers – planets and satellites: detection – radio lines: planetary systems – techniques: spectroscopic

1. INTRODUCTION

The first modern Search for ExtraTerrestrial Intelligence (SETI) was undertaken at radio wavelengths in 1960 at Green Bank, West Virginia (Drake 2008), targeting two stars, Tau Ceti and Epsilon Eridani at frequencies near the 21 cm line of neutral hydrogen.

In the decades since, SETI programs have continued to be undertaken at radio wavelengths, on the basis that highly sensitive radio telescopes exist for astronomy, the radio band is the cornerstone of communications technologies on Earth, and it could be reasonably assumed that a similar technology path has been taken by extraterrestrial civilizations. In 1985, the Million-channel ExtraTerrestrial Assay (META) was established at Harvard University (Leigh & Horowitz 1997), also near 1.4 GHz. META was upgraded to the Billion-channel ExtraTerrestrial Assay in 1995, in the extended frequency range of 1.4–1.7 GHz. The Search for Extraterrestrial Radio Emissions from the Nearby Developed Intelligent Populations (SERENDIP) program was established in 1978 and has evolved considerably since then (Werthimer et al. 2001). The SERENDIP program also gave rise to projects such as SETI@home (Korpela et al. 2009) and Southern SERENDIP (Stootman et al. 2000), a survey conducted using the Parkes radio telescope. A novel targeted search using Very Long Baseline Interferometry observations of the Gliese 581 star system is described by Rampadarath et al. (2012). The Allen Telescope Array has been used extensively for a range of SETI experiments over the last decade (Welch et al. 2009). Recently the ATA has conducted SETI experiments targetting over 9200 exoplanets (Harp et al. 2016a, 2016b). See Garrett (2015) for a recent review of aspects of SETI experiments at radio wavelengths. For general reviews, see Tarter (2003) and Siemion et al. (2015).

The SETI experiments conducted at radio wavelengths to date have generally focused on the 1.4–1.7 GHz range, the so-called “water hole” between the prominent radio spectral lines due to neutral hydrogen (H) and hydroxyl (OH). However, many other radio frequencies are also viable for SETI experiments. One radio frequency range that has opened up in recent years is in the tens to hundreds of MHz. Powerful multi-purpose, next-generation low-frequency radio telescopes such as the Low-frequency Array (LOFAR: van Haarlem et al. 2013) and the Murchison Widefield Array (MWA: Lonsdale et al. 2009; Tingay et al. 2013) are precursors and pathfinders for the billion dollar Square Kilometre Array (SKA: Dewdney et al. 2009) over the next decade. A key science program for the SKA is the “cradle of life” (Hoare et al. 2015), including comprehensive and ambitious SETI experiments (Siemion et al. 2015). Loeb & Zaldarriaga (2007) discuss the prospects for SETI experiments using facilities such as the MWA, LOFAR, and the low-frequency SKA, instruments that are primarily designed to search for the redshifted neutral hydrogen line from the Epoch of Reionization. Rahvar (2015) discusses the potential for utilising microlensing for SETI programs at radio wavelengths, with particular reference to the MWA and SKA. LOFAR, operating in the ranges of 30–80 MHz and 120–240 MHz, launched a SETI project in 2010,³ although no results have thus far been published.

The MWA operates in the frequency range of 80–300 MHz on an exceptionally radio quiet site in Western Australia. The high sensitivity of the MWA, its radio quiet location (Offringa et al. 2015), its frequency range, its access to the Southern Hemisphere, and its exceptionally large field of view (hundreds

³ <https://www.astron.nl/about-astron/press-public/news/lofar-opens-low-frequency-universe-and-starts-new-seti-search/lofar-o>

of square degrees) make it a unique facility for exploratory SETI experiments. As Garrett (2015) points out, the emergence of new radio telescopes with very large fields of view opens up new areas of parameter space for SETI experiments. For example, within a single >500 sq. deg. field of view typical for the MWA, on average tens of stellar systems within 50 lightyears will be accessible (ESA 1997). Based on recent results showing that planets are the norm rather than the exception, for example on average 1.0 ± 0.1 planets per M dwarf star in our Galaxy (Swift et al. 2013), one would therefore expect dozens of nearby (within 50 lightyears) planets in a single MWA field of view and far greater numbers of more distant planets. The MWA field of view, therefore, results in a significant multiplex advantage that can be exploited for SETI experiments.

While facilities such as the MWA, LOFAR, and the SKA will open up unprecedented parameter space for new SETI experiments, it is worth noting that the very first consideration of low radio frequency SETI came approximately 60 years before the first modern experiments described in Drake (2008), at the dawn of radio communications. In the late 1800s and early 1900s, Guglielmo Marconi⁴ and Nicola Tesla⁵ believed that radio waves could be used to communicate with civilizations on Mars (the widespread belief in the existence of Martian canals persisted at the time) and both claimed to have detected potential signals from that planet. In 1924, an experiment to listen for signals was organized by the US Navy during the opposition of Mars that year, coordinated with a planned cessation of terrestrial radio broadcasts.⁶ These very first low radio frequency experiments returned null results.

In this Letter, we present a first, and opportunistic, SETI pilot experiment with the MWA, in the frequency range 103–133 MHz, placing limits on narrowband radio emission toward 38 known planetary systems. The experiment is opportunistic in the sense that the observations were undertaken for a spectral line survey of the Galactic Plane that is ongoing; utility of the data for a SETI experiment was realized post-observation. We use this pilot study to motivate a deeper and significantly larger SETI experiment with the MWA, that could use the full 80–300 MHz frequency range and survey the entire southern sky (majority of the Milky Way) visible from Western Australia.

The field of SETI has recently received a substantial boost, with the “Breakthrough Listen” project recently initiated.⁷ Novel and diverse SETI experiments that sit on the path to utilization of the SKA for SETI, such as described here, are likely to be useful contributors to such initiatives.

2. OBSERVATIONS AND DATA ANALYSIS

The MWA system is described in Tingay et al. (2013), so we provide only a brief summary of the salient aspects of the observations. Observations with the MWA took place on 2014 July 25. Dual-polarization data were obtained in a 30.72 MHz contiguous bandwidth (consisting of 24×1.28 MHz contiguous coarse channels), centered at 119.7 MHz, with 10 kHz frequency resolution (thus 128 fine channels per 1.28 MHz

coarse channel). Observations took place in 5 minute segments over a total of 115 minutes, with pointing coordinates of R.A. = $17^{\text{h}}45^{\text{m}}40^{\text{s}}.036$ and decl. = $-29^{\circ}00'28''.17$ and a field of view (primary beam) full width at half maximum (FWHM) of $\sim 30^{\circ}$ at a resolution (synthesized beam) of $3'$. However, only 400 sq. deg. were imaged and searched, in order to make this first search a manageable size.

The edges of each coarse channel suffer from aliasing, requiring a number of fine channels on each coarse channel edge to be flagged. This resulted in approximately 78% of the 3072 fine channels being imaged. The central fine channel of each coarse channel was flagged, as they contain the DC component of the filterbank. Automated flagging of radio frequency interference (RFI) was performed using AO Flagger (Offringa et al. 2012) and a small number of fine channels were manually removed. In total, less than 0.5% of data were removed due to RFI, consistent with previous examinations of the RFI environment of the MWA (Offringa et al. 2015). As described in Tingay et al. (2015), AO Flagger only removes the strongest RFI, well above any limits on SETI signals discussed below. We also note that the RFI removed all corresponds to known terrestrial transmitter frequencies (generally FM radio and digital TV broadcast frequencies).

Calibration and imaging proceeded using the techniques described in Hurley-Walker et al. (2014). This includes using WS Clean (Offringa et al. 2014), using w-stacking to take into account the w-terms, to clean and image each individual fine channel with Briggs weighting set to -1 , a compromise between natural and uniform weighting to balance signal to noise and image resolution. The 100 individual fine channels from each coarse channel are imaged using 5.7 pixels per synthesised beam FWHM and were combined to produce a single data cube which was then converted into a MIRIAD (Sault et al. 1995) file format. In MIRIAD, all of the five-minute observations were time-averaged together to form a single data cube, representing an effective 82 minutes of integration time.

A continuum-subtracted image cube was produced, removing 99% of continuum emission using custom software. The field of view imaged for the cube was 400 sq. deg, covering the R.A. range $17^{\text{h}}03^{\text{m}}24^{\text{s}}-18^{\text{h}}28^{\text{m}}06^{\text{s}}$ and the decl. range $-18^{\circ}34'48''$ to $-38^{\circ}30'44''$. The rms noise levels in the continuum-subtracted cube (Table 1) were in line with theoretical noise estimates, calculated from the system description in Tingay et al. (2013).

Although an analytic model for a dipole over a ground screen has been used previously for primary beam correction with MWA data Hurley-Walker et al. (2014), we made no correction for the beam model in the creation of these data cubes, since this experiment is primary a detection experiment. To estimate the variation in expected flux densities, the data from the Molonglo Reference Catalog (MRC; Large et al. 1981), NRAO VLA Sky Survey (Condon et al. 1998), and Parkes-MIT-NRAO survey (Griffith et al. 1994) were compared to the flux density recovered for extragalactic sources in a non-continuum-subtracted image. This showed an error in the flux densities between 7% and 38% depending on angular distance from the phase center. In order to be conservative, the upper limits listed in Table 1 include a 40% error in the flux density scale.

A search of the field for exoplanets, based on the *Kepler* catalog (Akeson et al. 2013), returned 38 known planetary systems containing 45 exoplanets. The systems are listed in

⁴ Reported extensively in the media at the time, for example on page 3 of the New York Tribune, 1921 September 2: <http://chroniclingamerica.loc.gov/lcn/sn830302141921-09-02ed-1seq-3>.

⁵ <http://www.teslasociety.commars.pdf>.

⁶ <http://www.lettersofnote.com200911prepare-for-contact.html>

⁷ <http://www.breakthroughinitiatives.org/>

Table 1
The 38 Known Exoplanet Systems in the MWA Field of View

# System	R.A.	Decl.	rms (mJy)	Dist. (pc)	P (10^{13} W)
GJ 667 C	259.7451	-34.9968	529	6.8	<4
HD 156846	260.1429	-19.3337	461	49	<185
HD 164604	270.7789	-28.5606	488	38	<117
HD 169830	276.9562	-29.8169	453	36	<98
MOA 2007-BLG-192L	272.0158	-27.1501	457	1000	< 8×10^4
MOA 2007-BLG-400L	272.4249	-29.2242	470	5800	< 3×10^6
MOA 2008-BLG-310L	268.5605	-34.7781	461	6000	< 3×10^6
MOA 2008-BLG-379L	269.7060	-30.1969	443	3300	< 8×10^5
MOA 2009-BLG-266L	267.0081	-35.0054	454	3040	< 7×10^5
MOA 2009-BLG-319L	271.7422	-26.8197	465	6100	< 3×10^6
MOA 2009-BLG-387L	268.4616	-33.9903	448	5690	< 2×10^6
MOA 2010-BLG-073L	272.5473	-26.5229	489	2800	< 6×10^5
MOA 2010-BLG-328L	269.4963	-30.7152	467	810	< 5×10^4
MOA 2010-BLG-477L	271.5310	-31.4545	460	2300	< 4×10^5
MOA 2011-BLG-262L	270.0978	-31.2453	474	7000	< 4×10^6
MOA 2011-BLG-293L	268.9140	-28.4768	480	7720	< 5×10^6
MOA 2011-BLG-322L	271.2233	-27.2209	469	7560	< 4×10^6
MOA-bin-1L	261.7925	-29.7940	452	5100	< 2×10^6
OGLE 2003-BLG-235L	271.3181	-28.8950	478	5200	< 2×10^6
OGLE 2005-BLG-169L	271.5222	-30.7326	469	2700	< 6×10^5
OGLE 2005-BLG-390L	268.5800	-30.3773	474	6600	< 3×10^6
OGLE 2005-BLG-71L	267.5407	-34.6732	456	3200	< 8×10^5
OGLE 2006-BLG-109L	268.1438	-30.0878	469	1510	< 2×10^5
OGLE 2007-BLG-368L	269.1082	-32.2374	464	5900	< 3×10^6
OGLE 2008-BLG-355L	269.7867	-30.7595	476	6800	< 4×10^6
OGLE 2008-BLG-92L	266.8726	-34.7266	455	8100	< 5×10^6
OGLE 2011-BLG-251L	264.5591	-27.1361	469	2570	< 5×10^5
OGLE 2011-BLG-265L	269.4488	-27.3945	506	4380	< 2×10^6
OGLE 2012-BLG-26L	263.5779	-27.1428	453	4080	< 1×10^6
OGLE 2012-BLG-358L	265.6949	-24.2610	443	1760	< 2×10^5
OGLE 2012-BLG-406L	268.3257	-30.4712	472	4970	< 2×10^6
OGLE 2013-BLG-102L	268.0295	-31.6906	457	3040	< 7×10^5
OGLE 2013-BLG-341L B	268.0312	-29.8461	475	1161	< 1×10^5
OGLE 2014-BLG-124L	270.6217	-28.3963	470	4100	< 1×10^6
OGLE-TR-056	269.1480	-29.5392	478	1500	< 2×10^5
OGLE-TR-10	267.8677	-29.8764	475	1500	< 2×10^5
SWEEPS-11	269.7583	-29.1982	470	8500	< 6×10^6
SWEEPS-4	269.7247	-29.1891	473	8500	< 6×10^6

Note. Column 1: exoplanet system; column 2: R.A. (deg); column 3: decl. (deg); column 4: rms (mJy beam⁻¹); column 5: distance (pc); and column 6: upper limit on isotropic transmitter power in units of 10^{13} W.

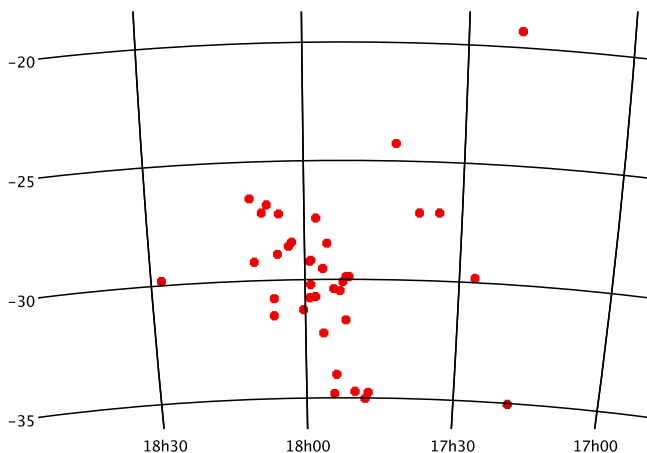


Figure 1. Distribution of the 38 known exoplanet systems in the MWA field of view.

Table 1 and are shown in relation to the MWA field of view in Figure 1.

The MWA data cube was searched at the locations of each of these exoplanet systems and spectra were extracted from these locations. No significant narrowband signals were detected above a 5σ level in any of these spectra. Table 1 lists the rms from the spectra at each of the exoplanet system locations and the corresponding 1σ limits on the inferred isotropic transmitter power required at the distance of the exoplanet system (ranging between 10^{14} and 10^{20} W). Figure 2 shows example spectra extracted from the MWA data cube, representing the four closest stars in Table 1: GJ 667; HD 156846; HD 164604; and HD 169830.

GJ 667, at 6.8 pc, is the closest star in Table 1. The closest recorded star to Earth in our field is 36 Ophiuchi, at a distance of 5.9 pc, which is not significantly closer than GJ 667 when considering the calculation of limits on transmitter power in

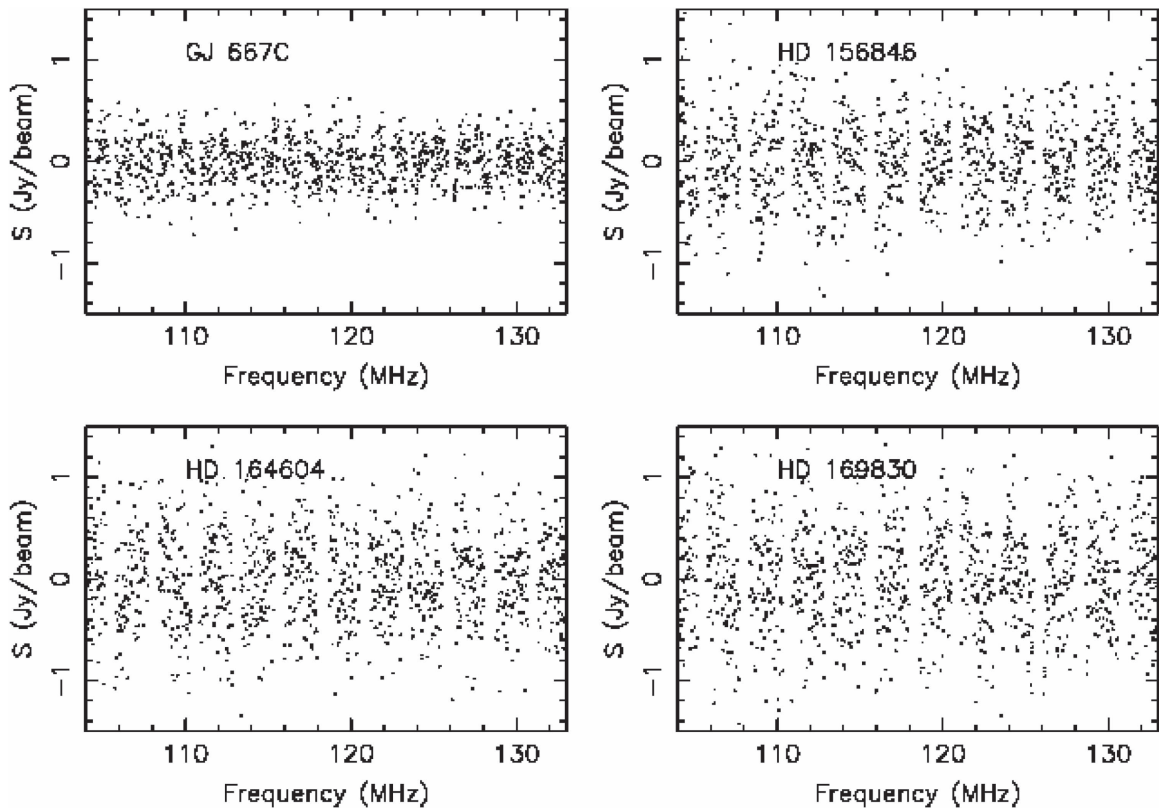


Figure 2. MWA spectra for the four closest exoplanet systems listed in Table 1. Areas of flagged fine channels on coarse channel edges are evident as gaps in the spectra.

Table 1. For the typical spectral rms in Table 1, four to five hundred mJy beam^{-1} , the corresponding limit for the nearest extrasolar star to the Earth (proxima Centauri, 1.3 pc—not in our field) would be approximately 10^{13} W.

3. DISCUSSION AND CONCLUSION

The great majority of exoplanet systems listed in Table 1 are at large distances, yielded from microlensing experiments toward the Galactic Center, meaning that the observational limits on detectable transmitter power from the MWA are very high, inferred isotropic powers of 10^{17} – 10^{19} W. Even if a directional transmitting antenna is assumed, with a gain similar to low-frequency over-the-horizon (OTH) radar transmitters on Earth, the limits on transmitter power are only reduced by factors of order 100.

A small handful of exoplanet systems in Table 1 are close enough that the inferred isotropic transmitter powers are of order 10^{13} – 10^{14} W. These are still very large in terms of transmitters on Earth. The highest power low-frequency transmitters on Earth are the OTH-backscatter radars used for military surveillance; these typically operate in the 5–30 MHz range and have transmitter powers of order 1 MW. For example, the Jindalee Operation Radar Network in Australia has a transmitter power of 560 kW (Colegrove 2000) and similar installations in the US, such as the AN/FPS-118 OTH-Backscatter radar,⁸ have transmitter powers of 1 MW (but can range up to 10 MW). In the latter case of the US system, the Effective Radiated Power is 100 MW, still a factor of $\sim 10^5$ below the limits for the nearest exoplanet systems in Table 1.

⁸ <http://www.globalsecurity.org/wmd/systems/an-fps-118.htm>

Even the addition of the signals from the ensemble of global array of OTH radars fall well below our limits. Loeb & Zaldarriaga (2007) summarize other Earth-based transmitter characteristics relevant to low-frequency telescopes.

The most powerful transmission ever deliberately broadcast into space was the Arecibo message, which was directed as a purposeful communication at the globular cluster M13, in a 10 Hz bandwidth at 2380 MHz (NAIC 1975). This transmission had an equivalent isotropic transmission of 20×10^9 W. Taking the narrow bandwidth into account (and ignoring the large difference in frequency), this transmission once again falls below the limits calculated in Table 1.

In the MWA frequency range, McKinley et al. (2013) previously estimated the Equivalent Isotropic Power of FM radio transmissions from the Earth to be 77 MW. This estimate was made by measuring the amount of stray FM radio signal reflected off the Earth’s moon. Again, this isotropic power is well below the limits in Table 1.

Of course, these projections of Earth-based technologies discount the possibility that higher power and/or more highly directive antenna technologies are utilized by advanced extraterrestrial civilizations for communications or remote sensing applications.

While the inferred transmitter powers in Table 1 are high compared with the most powerful low-frequency transmitters on Earth, this study has nonetheless provided the most comprehensive search for narrowband transmissions from exoplanets in this frequency range. Due to the southern, RFI free location of the MWA, its operational frequency range, and its wide field of view, the MWA provides a unique capability for future SETI projects.

This experiment examined one field of view of 400 sq. deg. in a 30.72 MHz frequency band. To perform a SETI experiment to the same depth as achieved here, but over the full MWA frequency range (80–300 MHz), and over the full accessible sky from Western Australia, would require approximately one month of observing time. This is an entirely feasible goal for the near future (three times deeper would require of order a year of observing). Moreover, to relieve the restriction of 10 kHz frequency resolution present in the current experiment, it is possible to record voltage data from the MWA and reconstruct coherent beams at far higher spectral resolution to target individual exoplanet systems Tremblay et al. (2015b). For example, generating 1 Hz channels from coherent beams across the full array would yield a factor of 100 improvement in sensitivity (assuming a 1 Hz transmission bandwidth), compared to the current experiment. Such a mode could be run communally with the large-scale survey described above, for a selected list of target systems.

The current experiment and the capabilities of the MWA provide a clear path to the far greater capabilities of the low-frequency component of the SKA, which will be built at the same location as the MWA and have a spectral sensitivity some tens of times greater than the MWA. The radio quiet nature of the MWA/SKA site in enabling SETI experiments at low frequencies (especially through the FM band), as demonstrated here, bodes well for SETI experiments with the SKA.

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Facility: MWA.

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