Nitric Oxide and Other Molecules: Molecular Modeling and Low-frequency Exploration Using the Murchison Widefield Array

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Abstract

We present new molecular modeling for $^{14}$NO and $^{15}$NO and a deep, blind molecular line survey at low radio frequencies (99–129 MHz). This survey is the third in a series completed with the Murchison Widefield Array (MWA), but in comparison with the previous surveys, uses 4 times more data (17 hr versus 4 hr) and is 3 times better in angular resolution (1$'$ versus 3$'$). The new molecular modeling for nitric oxide and its main isotopologue has seven transitions within the MWA frequency band (although we also present the higher-frequency transitions). Although we did not detect any new molecular lines at a limit of 0.21 Jy beam$^{-1}$, this work is an important step in understanding the data processing challenges for the future Square Kilometre Array and places solid limits on what is expected in the future of low-frequency surveys. The modeling can be utilized for future searches of nitric oxide.

Unified Astronomy Thesaurus concepts: Astrochemistry (75); Molecular spectroscopy (2095); Radio astronomy (1338); Surveys (1671); Interstellar medium (847); Interstellar molecules (849)

1. Introduction

Molecules are valuable tracers within our Galaxy to explore the chemical and physical environments of stars, dust, and gas. Published studies of molecular lines at low frequencies (<700 MHz) are rare (e.g., Marthi & Chengalur 2010) and have included the contributions made with the Murchison Widefield Array (MWA; Tremblay 2018). The science goals of these low-frequency detections include understanding the physical properties of the regions in which they are found, in particular those of high-mass star formation, and understanding the formation mechanisms of molecules, such as sulfur- and nitrogen-bearing molecules and amino acids (as the building blocks of life). The goal of this project is to both understand the molecules that may be present and push the surveys to deeper levels than previous work.

The understanding of high-mass (>8–10 $M_\odot$) star formation, which is still not well understood, can be improved by observations at frequencies less than 1 GHz (Codella et al. 2015). Seeing the need to understand the evolution of complex organic molecules in high-mass stars, Coletta et al. (2020) studied 39 H II regions with the IRAM 30 m Telescope that are in various stages of development. They found the largest number of detections in ultracompact (size: 0.05 $< R \leq$ 0.1 pc; density: n $\geq$ 10$^6$ cm$^{-3}$) H II regions. However, the higher temperatures in young high-mass stars create confusion from molecules that produce intense emission or a large number of transitions within the microwave and infrared frequency range, making it difficult to find new rare molecules. The lower-frequency part of the radio spectrum is far less crowded. In addition, as we approach the regime where the ratio of the level spacing to the thermal energy of the gas is very small (i.e., small $h\nu/kT$) it is possible that lines may be more readily inverted (e.g., Elitzur 1992), and we may wish to seek for signs of maser emission.

Therefore, a combination of surveys at the meter, centimeter, and millimeter wavelengths of the same regions of the sky, may unravel the mysteries of the formation mechanisms of high-mass stars through analysis of their chemical evolution. As high-mass stars have a large impact on the initial mass function and chemical enrichment of a galaxy, obtaining a better understanding of their evolution within our Galaxy is important to galactic archeology. With a combination of the low-frequency surveys with the MWA and new high-resolution surveys with the Australian Square Kilometre Array Pathfinder (Dickey et al. 2010), we can start to probe the southern sky, with access to the inner Galactic plane, in new detail.

From the molecular perspective, the motivation to observe at lower radio frequencies is not limited to complex molecules. Rare simple molecules, such as the free radicals, CH (∼724 MHz), SH (∼111 MHz), or NO (107.4 MHz—this work), are predicted to exhibit boosted emission similar to OH at 1.6 GHz (described more in Section 2) and were tentatively detected with our previous molecular line surveys with the MWA (Tremblay et al. 2017, 2018). Nitric oxide (NO) is of particular interest because is expected to be widespread in the interstellar medium (McGonagle 1995) and it plays an important role in the formation of hydroxylamine (H$_3$NO), which is an important molecule in the pathway of the formation of amino acids. Laboratory experiments have created enamines (precursors to amines) with deuterated formic acids in a neutral medium (Himmels et al. 1979), suggesting that the search for formic acid and nitric oxide may point to the production of amines within circumstellar environments. NO is also of particular interest as it is thought to be critically important to primitive life on Earth (Santana et al. 2017).
Despite this interest, and even with the precise frequencies of emission having been determined, little is known about the formation of NO or the primary emission frequencies we could expect to detect in interstellar space at meter wavelengths. Both Quintana-Lacaci et al. (2013) and Chen et al. (2014) summarize some theoretical modeling regarding the formation of NO in evolved stars. They suggest that NO forms in shocked gas surrounding asymptotic giant branch (AGB) stars and red supergiants (RSGs) within the layer inhabited by OH masers (typically located at distances of 5–50 R\(_{\odot}\)). They suggested a formation mechanism of OH + N \→ NO + H, which is a barrierless reaction. Cernicharo et al. (2014) suggest a similar reaction for the formation of NO in the diffuse interstellar medium. However, contained in the Kinetic Database for Astrochemistry (KIDA; Wakelam et al. 2012) are other possible formation routes of NO through cosmic-ray interaction, photodissociation, and bimolecular reactions.

In our previous surveys with the MWA we observed the Galactic center (Tremblay et al. 2017) and the Orion Molecular Cloud Complex (Tremblay et al. 2018). In this paper we focus on the region toward the Vela constellation. Prior to 1991 (Murphy & May 1991), the Vela constellation was thought to be devoid of the presence of spiral arms or spurs, with no star formation activity; however, it has since become a region of intense scientific interest. In the foreground is the wind-swept H\(_{\text{II}}\) region called the Gum Nebula, shown in the right panel of Figure 1 as an \(\sim18^\circ\) (Chanot & Sivan 1983; Purcell et al. 2015) bubble of intense H\(\alpha\) emission about 200 pc away. Then at an intermediate distance of about 400 pc–1 kpc (depending on the filament) is the Vela supernova remnant high-speed shock front (also known as the IRAS Vela Shell), shown in the left panel in radio continuum as a “flower-like” structure (Pakhomov et al. 2012). Finally, in the background is the Vela Molecular Cloud Complex, which has been the subject of a large number of molecular line studies due to its unique molecular structures between 1 and 2 kpc away. Yamaguchi et al. (1999) studied the region in CO and found 82 molecular clouds and a number of cometary globules. This has led us to study the region at low radio frequencies to see what we can unravel about its secrets.

In this paper we present new molecular modeling for NO transitions at frequencies between 3 and 4000 MHz (Section 2), together with a blind molecular line survey of the 192 known molecular transitions in the band of 99–129 MHz, over 200 deg\(^2\) toward the Vela region (Sections 3, 4, and 5). For the survey we use a total of 17 hr integration time, making it the deepest survey with the MWA to date. We then discuss the prospect for observations with Square Kilometre Array (SKA) Pathfinders and the SKA itself (Section 6).

2. Nitric Oxide

Interstellar NO (also known as nitrogen monoxide or the nitrosyl radical) was first observed by Liszt & Turner (1978) toward the star-forming, and hydroxyl (OH) maser-emitting, region of Sagittarius B2 using the 11 m Kitt Peak radio telescope at 150.2 and 150.5 GHz. Since then NO has been detected in thermal emission toward evolved stars (Quintana-Lacaci et al. 2013; Velilla Prieto et al. 2015), dark molecular clouds (Gerin et al. 1992), the interstellar medium (McGonagle 1995; Cernicharo et al. 2014), and star-forming regions (Ziurys et al. 1991). All of which are detected at hundreds of GHz frequencies. The only tentative detection of low-frequency maser emission was with the MWA toward the Galactic center (Tremblay et al. 2017) and Orion Molecular Cloud Complex (Tremblay et al. 2018).

Based on work done by Meerts & Dymanus (1972) and Meerts (1976), NO is one of the more prominent known molecules in the low-frequency range, being a highly reactive free radical. Despite little being known regarding which of the low-frequency molecular transitions are most likely to be detected in the interstellar medium, we would expect to see some at the frequencies detectable by the MWA. With this motivation, we present here new modeling of NO and its role in relation to known interstellar free radicals.
2.1. New Molecular Modeling

The similarity of the NO molecule to OH is due to the presence of a single unpaired electron, with one unit of orbital angular momentum and half a unit of spin, in both species. This results in two ladders of rotational levels, where the components of these angular momenta along the internuclear axis are aligned ($^3\Pi_{1/2}$, or $\Omega = 3/2$) and opposed ($^3\Pi_{3/2}$, or $\Omega = 1/2$). The lower-energy ends of these ladders, up to an energy of 133.5 cm$^{-1}$ (or 192 K), are shown in Figure 2 together with details of lambda doubling and hyperfine structure.

The similarity to OH is closest for the isotopologue $^{15}\text{N}^{16}\text{O}$, in which the nuclear spin of the $^{15}\text{N}$ is 1/2, as for the H-atom in OH. The resulting hyperfine structure has four levels per rotational level, with an F-quantum number that has integral values. The case of $^{14}\text{N}^{16}\text{O}$ is more complicated, because $^{14}\text{N}$ has a nuclear spin of 1. Groups of six hyperfine levels usually result, labeled by a half-integral F-quantum number, as shown in Figure 2; only four hyperfine levels are possible in the rotational ground state. The energy-level data for Figure 2 are drawn from the NO RADEX file in the Leiden Atomic and Molecular Database (Schöier et al. 2005) that in turn made use of data from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005). We note that the CDMS data use the Hund’s case (b) notation, instead of the case (a) notation used in the present work. Levels with the case (b) quantum number $N = J + 1/2$ equate to the $^3\Pi_{1/2}$ (and $N = J - 1/2$, to $^3\Pi_{3/2}$) for $J \leqslant 11/2$; the equivalence is reversed for higher $J$. The sign of the parity in the present work agrees with the Leiden file, and appears to be reversed with respect to Meerts & Dymanus (1972).

Figure 2 includes transition frequencies in MHz for all hyperfine transitions that change parity. Additional transitions that do not change parity, but appear in the Leiden RADEX file and have frequencies in the MWA range, are also shown. Transition data were cross-referenced from the Leiden file to data tables in Meerts & Dymanus (1972). Frequencies followed by an asterisk appear in neither the Leiden file nor the tables in Meerts & Dymanus (1972), but were taken directly from the CDMS database. Transitions of NO within or near to the frequency range of the MWA are listed with more accurate frequencies and additional information in Table 1.

In summary, the intricate hyperfine and lambda doubling structure of NO, combined with its increased mass relative to OH and CH, leads to the presence of many allowed transitions with frequencies <1 GHz that may be excited under typical interstellar and circumstellar temperatures. Many would be suitable candidates for low-frequency instruments, such as the MWA. Some NO transitions are, in fact, well below the ionospheric plasma frequency ($\sim$30 MHz). This new representation of the energy levels of NO will be used to motivate searches for the transitions identified, both with the MWA and at higher frequencies with SKA pathfinders, especially where simultaneous searches for NO, CH, and OH may be possible.

3. Observations

The MWA (Tingay et al. 2013; Wayth et al. 2018) consists of 256 tiles, of 16 dipoles each, arranged on the Murchison Radio-astronomy Observatory in Western Australia. The Phase-I array consisted of 128 dipole aperture tiles spread over 3 km with a compact core. The Phase-II expanded array adds an additional 128 tiles, 56 of which are used to extend the baselines to 5.5 km. During these observations only 91 tiles were online during building and commissioning of the Phase-II array with baselines between 1.5 and 5.5 km. The dipoles themselves do not move, and the mechanism to observe in the direction of a given source is to electronically apply delays.
Whenever the control software determines the source is outside the sensitive region of the primary beam, the delays are reset at quantized values. This means that each 5 minute observation samples a slightly different patch of sky.

3.1. Data Processing

Each observation is calibrated using a 2 minute observation of Hydra A (a radio galaxy with a flux density of 243 Jy at 160 MHz; Kühr et al. 1981) from the beginning of each night. The bandpass and phase solutions are further refined using self-calibration of the calibrator field prior to applying the corrections to the observations of the target field. Each of the 5 minute observations of the target field are processed by first imaging each of the polyphase filter bank coarse channels (1.28 MHz \times 24) to check the data quality of the set of observations. Of the nine nights of observation (for a total of 30 hr) between 2018 January 5 and 2018 January 23, four nights were not used, as they were impacted by severe radio frequency interference (RFI). Normally the RFI environment of the Murchison Radio-astronomy Observatory is clean, but occasionally there are nights of periodic strong interference (Ofiringa et al. 2015; Sokolowski et al. 2017).

For each of the remaining nights of observation, 100 of the 10 kHz fine frequency channels per 1.28 MHz coarse channels are imaged (for a total of 2400 channels) across the 30.72 MHz bandwidth. This frequency resolution corresponds to a velocity resolution of 24–30 km s^{-1} for objects within our own Galaxy. The reason for only imaging 75% of the band is to avoid fine frequency channels known to be affected by aliasing due to the filter bank used to channelize the data.

The Phase-II configuration of the MWA used in these observations removed the compact core and had shortest baselines of 1.5 km. In order to obtain as much sensitivity to the diffuse emission as possible, all of the images were created using a Briggs weighting of “0.5” closer to natural weighting than uniform weighting. Due to the large volume of data, it was not practical to process them using different weightings for this survey, even though the angular resolution was slightly compromised.

Upon completion of the imaging of each fine channel for each observation, the channel images are combined into a three-dimensional data cube using software written in PYTHON. All of the cubes for all of the observations are then integrated together using the MIRIAD (Sault et al. 1995) program IMCOMB. For greater detail on the data processing see Tremblay et al. (2018).

Free electrons in the Earth’s atmosphere can create spatially varying refraction and propagation delays that are significant at low radio frequencies (<1 GHz). For each 5 minute observation, the estimated source positions are compared to the Molonglo Reference Catalogue (MRC; Large et al. 1981) to correct for shifts in apparent positions. After correction, the systematic spatial error in a fully integrated continuum image was \(-10 \pm 26"\) in R.A. and \(+6 \pm 11"\) in decl.. Both of these values are smaller than the synthesized beam of 1'03. The ratio of point-source flux density and peak intensity is 1.05. This suggests that the ionospheric distortions are corrected well in these observations.

3.2. Continuum Subtraction and Flagging

The continuum signal in the cubes is formed from a combination of diffuse Galactic structure, including the Vela and Puppis supernova remnants, and hundreds of background extragalactic point sources, as well as the nondeconvolved sidelobes of structures both inside and outside the field of view. It varies slowly and smoothly along the frequency axis, except at the edges of the coarse channels, which are flagged. To calculate the continuum to be subtracted from the cubes, we calculate a moving boxcar median along the spectral axis, across a range of 200 kHz (20 fine channels). For channels that are within 100 kHz of a coarse channel edge, we use the median value of the channel exactly 100 kHz from the coarse channel edge. The resulting continuum cube is subtracted from the original cube to produce a noise-like cube that can be searched for spectral lines.

At this stage, channels with RFI contamination are easily identified by their high rms. We calculate the mean rms along the spectral axis and flag any channel that has noise 20% higher than the mean value, repeating this process three times. These flags are applied to the original data cube, and then the continuum subtraction is performed again. This ensures that RFI does not contaminate the continuum estimate. The first coarse channel (\(~99.2–100.5\) MHz) was entirely flagged for RFI and not used for further analysis.

Table 1

| \(\nu\) (MHz) | Upper Level \((^{2}J_{10}, J = f', F(P))\) | Lower Level \((^{2}J_{10}, J = f'', F(P))\) | \(N_{u}\) | \(N_{l}\) | \(T_{\text{up}}\) (K) | Einstein A (Hz) | Notes |
| --- | --- | --- | --- | --- | --- | --- | --- |
| 73.2860 | \(^{2}J_{3/2}, J = 3/2, \frac{1}{2}(-)\) | \(^{2}J_{3/2}, J = 3/2, \frac{3}{2}(+)\) | 51 | 50 | 179.7216 | \(1.08 \times 10^{-17}\) |  |
| 74.9310 | \(^{2}J_{3/2}, J = 3/2, \frac{3}{2}(+)\) | \(^{2}J_{3/2}, J = 3/2, \frac{3}{2}(-)\) | 52 | 49 | 179.7261 | \(1.18 \times 10^{-17}\) |  |
| 80.1814 | \(^{2}J_{7/2}, J = 7/2, \frac{1}{2}(+)\) | \(^{2}J_{7/2}, J = 7/2, \frac{3}{2}(+)\) | 22 | 21 | 36.12975 | \(8.25 \times 10^{-20}\) | \(\Delta P = 0\) |
| 88.1111 | \(^{2}J_{5/2}, J = 5/2, \frac{1}{2}(+)\) | \(^{2}J_{5/2}, J = 5/2, \frac{3}{2}(+)\) | 16 | 15 | 19.28224 | \(8.73 \times 10^{-20}\) | \(\Delta P = 0\) |
| 107.3682 | \(^{2}J_{3/2}, J = 3/2, \frac{3}{2}(+)\) | \(^{2}J_{3/2}, J = 3/2, \frac{1}{2}(+)\) | 10 | 9 | 7.24584 | \(7.99 \times 10^{-20}\) | \(\Delta P = 0\) |
| 205.9510 | \(^{2}J_{1/2}, J = 1/2, \frac{1}{2}(+)\) | \(^{2}J_{1/2}, J = 1/2, \frac{3}{2}(+)\) | 3 | 2 | 0.01079 | \(9.51 \times 10^{-17}\) |  |
| 225.9357 | \(^{2}J_{1/2}, J = 1/2, \frac{3}{2}(+)\) | \(^{2}J_{1/2}, J = 1/2, \frac{1}{2}(+)\) | 3 | 1 | 0.01079 | \(1.00 \times 10^{-15}\) |  |
| 411.2056 | \(^{2}J_{1/2}, J = 1/2, \frac{3}{2}(+)\) | \(^{2}J_{1/2}, J = 1/2, \frac{1}{2}(+)\) | 4 | 2 | 0.02064 | \(3.02 \times 10^{-15}\) |  |
| 431.1905 | \(^{2}J_{1/2}, J = 1/2, \frac{1}{2}(+)\) | \(^{2}J_{1/2}, J = 1/2, \frac{3}{2}(+)\) | 4 | 1 | 0.02064 | \(4.34 \times 10^{-15}\) |  |

Note. The \(N_{u}\) and \(N_{l}\) refer to the energy order levels from Figure 2. Frequencies are taken from the Leiden database. An entry \(\Delta P = 0\) in the final column indicates a parity-conserving transition. Transitions of this type are included in the table only if they are in the observable frequency range of the MWA.

The Astrophysical Journal, 905:65 (8pp), 2020 December 10

Tremblay et al.
noise, and it is only the long integration time and the dense
spurious values of up to 7σ can appear in these cubes. This is
not unexpected, as most interferometric data has non-Gaussian
statistics. A similar analysis of all the cubes shows that
pixels with values in excess of those predicted by Gaussian
distribution so close to Gaussian.

3.3. Survey Statistics

To search these data for lines, i.e., determine what signals are
significant, we must first examine the properties of the noise in
the data. Figure 3 shows an image of the spatial distribution of
the rms noise, for the flagged and continuum-subtracted
107.02–108.02 MHz cube; the other channels look similar.
The sensitivity of the stacked cube varies by over a factor of 2
over the region, due to the combination of many different fields
of view with different primary beam sensitivities. There are no
visible artifacts from the continuum subtraction or RFI flagging.
To examine the noise in more detail, we select a region of
roughly constant noise, highlighted by a white box in Figure 3.

There are 24 coarse channel cubes, each comprising
100 × 10 kHz channels, and subtending 2500 × 2500 pixels.
Since interferometers produce images that are correlated on the
scale of the synthesized beam, to obtain the number of
independent samples, we must divide by the synthesized beam
volume 4πab2, where a and b are the major and minor FWHMs
of the synthesized beam: 165″ and 92″, respectively. Before
flagging, there are therefore about 700 million independent samples to search for lines. The flagging process described in
Section 3.2 removes 201 of the 2400 initial channels, leaving
641 million independent samples.

Figure 4 shows a histogram of the pixel values in the white
boxed region selected in Figure 3 compared to a Gaussian
distribution of the same standard deviation. While the central
part of the histogram resembles a Gaussian, the tails contain
pixels with values in excess of those predicted by Gaussian
statistics. A similar analysis of all the cubes shows that
spurious values of up to ±7σ can appear in these cubes. This is
not unexpected, as most interferometric data has non-Gaussian
noise, and it is only the long integration time and the dense (u,
v)-coverage of the MWA (Wayth et al. 2018) that makes the
distribution so close to Gaussian.

3.4. Source Finding

Each of the 2400 continuum-subtracted fine-channel
(10 kHz) images are independently searched using the source-
finding software AEGEAN (Hancock et al. 2018). This is done
using the function “slice,” to set which channel in the cube is
searched, and setting a “seed clip” value of 5, in order to search the
image for pixels with a peak intensity value greater than 6σ
(where σ is set from an input rms image such as that shown in
Figure 3). This source-finding threshold, based on the results of
Section 3.3, has the goal of detecting all signals >7σ.

4. Survey Strategy

A blind spectral line survey of ~200 deg² was completed with
the MWA across the bandwidth of 98–129 MHz. In this band there
are 196 known molecular transitions with upper energies less than
300 K. However, there has been little assessment of which of these
lines are likely to be found in astrophysical environments. We use
the limit of 300 K as above this limit it is expected that the
transitions would be unlikely to be detectable in astrophysical
environments, as the number of molecules within these kinetic
temperatures is likely small. Figure 5 shows the full spectrum of
the band with vertical lines showing the population density of the
known transitions. Of the known transitions, most of the rest
frequencies are calculated theoretically and there are often only one
or two lines for each molecular species. To identify potential peaks
in the survey, we used the following databases: Cologne Database
for Molecular Spectroscopy (CDMS; Müller et al. 2001), Spectral
Line Atlas of Interstellar Molecules (SLAIM; Splatalogue8), Jet
Propulsion Laboratory (JPL; Pickett et al. 1998), and Top
Model (Carvajal et al. 2010).

5. Results

At a significance level of 7σ we did not detect any signals in emission. This is a limit of approximately 0.21–0.35 Jy beam⁻¹
(depending on the specific region) and is a flux density limit that matches (or is above) our previous tentative detections in
our surveys toward the Galactic center and Orion. This translates to a single-channel upper limit of 26,760 K km s⁻¹

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8 https://www.cv.nrao.edu/php/splat/index.php
for the 107 MHz transition of NO. This would also mean the column densities would be higher than the upper limit set in Tremblay et al. (2017). It is therefore unsurprising that we did not detect anything at this level. In this survey we use the early science data from Phase II, while the previous survey was done with Phase I in a stable state after years of operation. Also, with the extended baselines we are more sensitive to different emission (dense gas versus diffuse).

It is possible that some features may be in absorption against strong continuum. To assess if we detect any absorption features, we created spectra toward five of the brightest continuum sources in the field, consisting of the Puppis supernova remnant, star LBS72 Star E, the radio continuum objects CUL 0836-443 (Slee 1995) and PMN J0820-4736 (McConnell et al. 2012), and the HII region RCW 38. We found the continuum emission brightness varied for these sources from 0.4 to 7 Jy beam$^{-1}$ with a median optical depth limit of 0.22 ± 0.13. Within the non-continuum-subtracted data cubes, no signals were detected over a 7σ limit in absorption.$^9$

6. Discussion

It is known that low-frequency molecular lines are weak emitters (e.g., Codella et al. 2015), which makes this type of

$^9$ We note that the higher noise is a result of residual bandpass structure around bright continuum sources that is normally corrected for in the continuum subtraction.
experiment, in particular with a 24 km s\(^{-1}\) velocity resolution, a
difficult one. However, low-frequency transitions are, in
general, relatively easy to invert (e.g., Elitzur 1992), making
the MWA frequency range a potentially interesting hunting
ground for new masers.

One of the largest molecules of interest by the astrochemical
community is the amino acid glycine (NH\(_2\)CH\(_2\)COOH). Codella
et al. (2015) predict that to observe glycine at centimeter
wavelengths would require over 1000 hr of observation to obtain
a 3\(\sigma\) detection. This is a considerable effort in data processing,
as well as the observing time commitment. Our survey represents a
start in understanding some of these data challenges as we
approach the era of the SKA.

In this survey, the \(~30\) hr of observations taken in 5 minute
snapshots represents around 360 individual raw visibility data
sets. Each data set was calibrated, and the continuum image
was created for each of the 24 coarse frequency bands. For any
observation or night of observations that were affected by
imaging artifacts or severe RFI, no further processing was
completed. For the remaining observations, each of the 2400
fine frequency channels were independently imaged. This
created more than 443,000 continuum images and used over
350,000 CPU hours on the “Magnus” computing cluster at the
Pawsey SuperComputing Centre and over 300 TB of disk
space. This represents significant computing resources for a
single project. These values do not include the resources
required to then search and create visual representations for
scientific analysis.

Additional challenges regarding spectral line data processing
with SKA precursors include making compromises on data
quality, field of view processed, or number of spectral channels
processed based on amount of RAM, processing time, and
read/write speeds on the computer. This limits the amount of
data taken by the telescopes that are available for actual science
and impacts blind surveys such as this. There are also
significant challenges regarding visualizing data cubes that are
hundreds of GB in size. This is being addressed by the
community with new tools like CARTA (Comrie et al. 2020).
The requirements for this style of data processing are not likely
to get smaller with the next generation of telescopes; it is
therefore important to understand the data processing
challenges with surveys such as this.

7. Conclusion

This work had two goals: to complete a deeper survey with
the MWA than previously attempted, and to increase our
knowledge of emission lines of \(^{14}\)NO and \(^{15}\)NO. We completed
a deep spectral line survey toward the Vela region, but found
no signals at a peak intensity limit of 0.21 Jy beam\(^{-1}\). This
survey is the third in a series completed with the MWA, but the
first using the new extended baselines, for an improved
resolution of 1\(\prime\) (versus the original 3\(\prime\)). We have also found that
the noise no longer decreases as a function of the square root of
time, suggesting that other improvements in the data processing
are required to obtain a better result. It is likely the noise is
limited to the deconvolution of individual snapshot images of the
fine frequency channels.

The molecular modeling presented in Section 2 for NO gives
us precise frequency targets to search for with the MWA and
other SKA precursor instruments, like the Parkes 64 m Telescope
and the Australia Square Kilometre Array Pathfinder. Many of
the new lines are within the frequency range of the new Parkes
ultra-wideband receiver (704–4032 MHz, Hobbs et al. 2020),
making it an interesting choice for future simultaneous searches of
NO, CH, and OH.

Overall, we present this work as an important step in
understanding the data processing challenges we will face with
the Square Kilometre Array and places solid limits on what can
be expected for these low-frequency surveys in the future.

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Astrophysics Data System Bibliographic Services. The kinetic
data we used have been downloaded from the online database
KIDA (Wakeham et al. 2012; http://kida.obs.uj-bordeaux1.fr).

Software: The following software was used in the creation of the
data cubes: AOFLAGGER and COTTER (Offringa et al. 2015),
WSCLEAN (Offringa et al. 2014; Offringa & Smirnov 2017),
AEGEAN (Hancock et al. 2018), MIRIAD (Sault et al. 1995),
TOPCAT (Taylor 2005), NumPy v1.11.3 (Dubois et al. 1996),
AstroPy v2.0.6 (Astropy Collaboration et al. 2013), SciPy
v0.17.0 (Oliphant 2007), Matplotlib v1.5.3 (Hunter 2007),
CARTA (Comrie et al. 2020).

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7
