Survey of Water and Ammonia in Nearby Galaxies (SWAN): Resolved Ammonia Thermometry, and Water and Methanol Masers in the Nuclear Starburst of NGC 253

Mark Gorski1,2, Jürgen Ott1, Richard Rand3, David S. Meier1,3, Emmanuel Momjian1, and Eva Schinnerer4

1 National Radio Astronomy Observatory, P.O. Box O, 1003 Lopezville Road, Socorro, NM 87801, USA; mgorski@unm.edu, jott@nrao.edu, emomjian@nrao.edu
2 Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Boulevard NE, Albuquerque, NM 87131, USA; rjr@unm.edu
3 Department of Physics, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, USA; david.meier@nmt.edu
4 Max-Planck Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; schinner@mpia.de

Received 2016 November 2; revised 2017 May 17; accepted 2017 May 18; published 2017 June 22

Abstract

We present Karl G. Jansky Very Large Array molecular line observations of the nearby starburst galaxy NGC 253, from SWAN, the Survey of Water and Ammonia in Nearby galaxies. SWAN is a molecular line survey at centimeter wavelengths designed to reveal the physical conditions of star-forming gas over a range of star-forming galaxies. NGC 253 has been observed in four 1 GHz bands from 21 to 36 GHz at 6′′ ~ 100 pc spatial and 3.5 km s⁻¹ spectral resolution. In total we detect 19 transitions from 7 molecular and atomic species. We have targeted the metastable transition of ammonia (NH₃) from (1, 1) to (5, 5) and the (9, 9) line, the 22.2 GHz water (H₂O) (6₋5₋₂₋₂) maser, and the 36.1 GHz methanol (CH₃OH) (4₋₃₋₃₋₃) maser. Using NH₃ as a thermometer, we present evidence for uniform heating over the central kpc of NGC 253. The molecular gas is best described by a two kinetic temperature model with a warm 130 K and a cooler 57 K component. A comparison of these observations with previous ALMA results suggests that the molecular gas is not heated in photon-dominated regions or shocks. It is possible that the gas is heated by turbulence or cosmic rays. In the galaxy center we find evidence for NH₃(3, 3) masers. Furthermore, we present velocities and luminosities of three water maser features related to the nuclear starburst. We partially resolve CH₃OH masers seen at the edges of the bright molecular emission, which coincides with expanding molecular superbubbles. This suggests that the masers are pumped by weak shocks in the bubble surfaces.

Key words: galaxies: individual (NGC 253) – galaxies: ISM – galaxies: nuclei – galaxies: starburst – ISM: molecules – radio lines: galaxies

1. Introduction

Physical descriptions of how the interstellar medium (ISM) condenses to form stars, and the resulting feedback from star formation, limit our understanding of galaxy evolution and the star formation history of the universe. Models of galaxy evolution without feedback drastically overpredict star formation rates (SFRs) and efficiencies. Feedback is necessary to impede star formation, otherwise, a galaxy reaches its peak SFR in less than a dynamical time and quickly converts its baryons into stars shortly after (e.g., Kauffmann et al. 1999; Hopkins et al. 2011; Krumholz et al. 2011). Star formation is largely correlated with the amount of dense, ³¹⁰⁴ cm⁻³, molecular gas within a galaxy (e.g., Gao & Solomon 2004), and in simulations the state of such gas is limited by the resolution of each individual simulation, i.e., subgrid physics (e.g., Okamoto et al. 2005; Haas et al. 2013; Crain et al. 2015). Consequently, understanding the relationship between star formation, the resulting feedback, and the state of the dense molecular gas is critical to understanding the star formation history of a galaxy.

Feedback in the star-forming ISM perturbs molecular gas such that it can no longer collapse and form new stars. Heating from supernovae, stellar winds, and photoionization are examples of the most dominant forms of stellar feedback (e.g., Kauffmann et al. 1999; Hartmann et al. 2001; Vázquez-Semadeni et al. 2010). One-dimensional simulations by Murray et al. (2010) suggest that different mechanisms dominate at different times during the lifetime of star-forming giant molecular clouds (GMCs). Furthermore, simulations by Hopkins et al. (2012) and Hopkins et al. (2014) show that these different feedback effects compound in a nonlinear way and that no single feedback process dominates the star-forming ISM. Additionally, the environment in which star-forming material exists may play a critical role in its properties. Therefore, observational constraints are necessary to refine the subgrid physics within the theoretical models on the appropriate scales.

Nearby galaxies provide access to scales of tens of pc where observations can reveal how feedback operates. Many studies have examined different aspects of feedback. For example, in NGC 253, Strickland et al. (2002) and Westmoquette et al. (2011) discuss the X-ray and ionized gas properties of a starburst-driven outflow, respectively. Studies of NH₃, such as those by Ott et al. (2005), Lebrón et al. (2011), and Mangum et al. (2013), reveal heating and cooling of the molecular ISM. In addition, other molecular tracers reveal shocks, photon-dominated regions (PDRs), masses, lengths, and timescales associated with star formation (e.g., Leroy et al. 2015; Meier et al. 2015).

The Survey of Water and Ammonia in Nearby galaxies (SWAN) is a survey of molecular line tracers at centimeter wavelengths that is designed to reveal the physical conditions in star-forming gas. The sample consists of four star-forming galaxies: NGC 253, IC 342, NGC 6946, and NGC 2146, and it was chosen to span a range of galaxy types from Milky Way-like to starbursts and an order of magnitude of SFRs from (≤ 1 M₉sun yr⁻¹) to starbursts (~10 M₉sun yr⁻¹). Here we discuss the first results from SWAN and focus on VLA K- and Ka-band observations of NGC 253.
NGC 253 has been studied at many wavelengths: X-ray (e.g., Strickland et al. 2002), optical (e.g., Westmoquette et al. 2011), infrared (e.g., Dale et al. 2009), millimeter (e.g., Bolatto et al. 2013 & Meier et al. 2015), and radio (e.g., Ulvestad & Antonucci 1997). Figure 1 shows a Spitzer 8 μm image of NGC 253 (Dale et al. 2009). The inset shows the central kpc with 3, 6, and 9σ contours of NH3(3, 3) emission from our data, which we discuss in Section 3.2.1. We adopt a distance of 3.5 Mpc measured from the tip of the red giant branch (RadburnSmith et al. 2011) and a systemic velocity of 234 km s⁻¹ in the LSRK frame from Whiting (1999). All velocities in this paper are given in the LSRK frame unless otherwise stated. The disk is inclined at i ≈ 78° (Pence 1980). NGC 253 has a total SFR of ~5.9 $M_\odot$ yr⁻¹, approximately half of which is concentrated in the central kpc (McCormick et al. 2013). The starburst is driving a massive molecular outflow, with a mass-loss rate estimated at 9 $M_\odot$ yr⁻¹, which is thought to be starving the current star-forming event (Bolatto et al. 2013). The outflow is also seen in X-rays (Strickland et al. 2002) and Hα (Watson et al. 1996). Sakamoto et al. (2006) found evidence for two expanding molecular superbubbles within the central kpc with kinetic energies on the order of ~10⁷⁶. Ott et al. (2005) and Bolatto et al. (2013) found several smaller molecular superbubbles in the same region. Bolatto et al. (2013) suggest that superbubbles and supernovae from the starburst drive the wind, whereas Westmoquette et al. (2011) favor a cosmic ray driven wind on the larger scales with a small contribution from the starburst in the center, with the molecular gas in the center responsible for collimating the outflow.

Centimeter and millimeter wavelength spectra of galaxies provide access to diagnostically important molecular tracers. The molecular gas is often well traced by CO, but more complex molecules can provide better tracers of gas properties such as temperature and density, and can be used to trace specific conditions such as PDRs and shocks (e.g., Fuente et al. 1993; García-Burillo et al. 2000; Meier & Turner 2005, and Meier et al. 2015). This study focuses on the metastable transitions ($J = K$) (1, 1) to (5, 5) and (9, 9) of NH3, the 22 GHz H2O(6_16−5_23) maser, and the 36 GHz CH3OH (4_1₄−3_0₃) maser. We use a combined analysis of these lines to expose the processes that dominate the central kpc of NGC 253.

The NH3 molecule generally works well as a temperature tracer of the molecular gas. The tetrahedral structure of NH3 makes it a symmetric top, meaning that the energy states are described by the rotation angular momentum quantum number J and the projection along the symmetry axis K. The J = K states, called metastable states, are long lived compared to J > K states, and population exchanges between K ladders are forbidden except by collisions. When NH3 is collisionally excited (critical density $n_{H_2} \geq 10^3$ cm⁻³), the K ladders are therefore expected to be populated in accordance with the kinetic temperature of the gas. As a result, measurements of the relative intensities of metastable states act as probes of the rotation temperature of the gas (e.g., Ho & Townes 1983; Walmsley & Ungerechts 1983; Ott et al. 2005, 2011; Lebrón et al. 2011; Mangum et al. 2013).

The NH3(3, 3) state can be a maser transition (Walmsley & Ungerechts 1983), but it is less well studied than other masers. In the Galaxy there is a weak association of NH3(3, 3) masers with dense gas in star-forming regions (e.g., Wilson & Mauersberger 1990; Mills & Morris 2013; Goddi et al. 2015). Here we use metastable transitions of NH3 to understand the heating and cooling balance of the dense molecular ISM in NGC 253.

The H2O and CH3OH masers provide a unique opportunity to probe star-forming environments. The H2O line requires gas densities >10⁷ cm⁻³ and kinetic temperatures >300 K to mase (e.g., Tarchi 2012). In the Galaxy these masers are typically found in shocked regions around young stellar objects (YSOs) and asymptotic giant branch (AGB) stars.
CH$_3$OH masers are found in high-mass star-forming regions (Lo 2005; Reid et al. 2009; Moscadelli 2006) (precisely tracing kinematics of stellar winds of hot, dense, and accretion disks). In Section 2, we report our measurements of the NH$_3$, H$_2$O, and CH$_3$OH lines. The 36.2 GHz CH$_3$OH line studied here is a Class I type maser. We mostly use these masers as signposts of shocked material. In addition to precisely tracing kinematics of stellar winds (e.g., Goddi & Moscadelli 2006) and accretion disks (e.g., Peck et al. 2003; Lo 2005; Reid et al. 2009).

Class I (collisionally pumped) and II (radiatively pumped) CH$_3$OH masers are found in high-mass star-forming regions (e.g., Ellingsen et al. 2012) and supernova remnants (e.g., McEwen et al. 2014) in the Galaxy. The Class I masers trace shocks and gas densities $>10^4$ cm$^{-3}$ (Pratap et al. 2008). The 36.2 GHz CH$_3$OH line studied here is a Class I type maser. We mostly use these masers as signposts of shocked material.

In Section 2 we describe the observational setup. In Section 3 we report our measurements of the NH$_3$, H$_2$O, and CH$_3$OH lines in addition to a brief description of the continuum and the H$_{56}\alpha$ radio recombination line (RLR). In Section 4 we discuss the derivation of temperatures across the molecular bar, the relevance of the H$_2$O masers to the outflow, the significance of the CH$_3$OH masers, and a comparison with previous ALMA millimeter molecular lines. Last, we summarize our findings in Section 5.

2. Observations and Data Reduction

We observed NGC 253 with the 18–26.5 GHz and 26.5–40 GHz (K and Ka band) receivers of the Karl G. Jansky Very Large Array (VLA)$^5$ (project code: 13A–375). The K-band observations were carried out on 2013 May 11. The Ka-band observations were split into two sessions: 2013 May 23 and May 26. The VLA was in the DnC hybrid configuration for all these observations. This configuration delivers a rounder beam for low-declination sources because the north arm is in the more extended C configuration, while the east and west arms are in D configuration. The received signal is sampled at each antenna using the eight-bit samplers. These provide two 1 GHz baseband pairs with both right- and left-hand circular polarizations. The correlator was set up to divide each baseband into eight sub-bands each with 512 channels, resulting in a channel width of 250 kHz. This yields a velocity resolution ranging from 3.0 to 3.3 km s$^{-1}$ for the K-band and 2.0–2.7 km s$^{-1}$ for the Ka-band observations. The baseband pairs were centered at 21.8 and 24.1 GHz in K band and at 27.1 and 36.4 GHz in Ka band. They are referred to here as the 22, 24, 27, and 36 GHz basebands, respectively. These were chosen to include the metastable NH$_3$ transitions from (1, 1) with rest frequency 26.6946 GHz, to (5, 5) at 24.5330 GHz, as well as (9, 9) at 27.4779 GHz, the H$_2$O($6_{16}$–$5_{15}$) maser line at 22.2351 GHz, and the CH$_3$OH($4_{24}$–$3_{03}$) transition at 36.1693 GHz. All of the detected lines and their rest frequencies are listed in Table 1. The on-source time for the K-band and Ka-band observations was 4.4 hr and 3.6 hr, respectively. We used 3C48 as the flux density calibrator, Perley & Butler (2013), J2253+1608 as the bandpass calibrator, and J0025-2602 as the complex gain calibrator in all observations. We alternated between 10-minute intervals on NGC 253 and 1.5-minute intervals on the complex gain calibrator.

The data were reduced in the Common Astronomy Software Applications package version 4.2.2 (McMullin et al. 2007). At the adopted distance of 3.5 Mpc, the linear scale is $\approx 17$ pc per arcsecond. The half-power primary beam widths of the VLA for the K and Ka bands are 2.1 ($\sim 2$ kpc) and 1.5 ($\sim 1.5$ kpc), respectively. All data cubes were gridded with 0$''$25 pixels, mapped using natural weighting, CLEANed to $\sim 3\sigma$ rms noise, and were regridded to a common velocity resolution of 3.5 km s$^{-1}$. Continuum subtraction was performed in the UV domain. For the 24 GHz baseband, several baselines were flagged for being noisy, yielding a slightly larger synthesized beam than the 22 GHz baseband. The resulting image cubes were then smoothed to a common synthesized beam of 3.0–3.3 km s$^{-1}$ for all these observations. This configuration delivers a rounder beam for low-declination sources because the north arm is in the more extended C configuration, while the east and west arms are in D configuration. The received signal is sampled at each antenna using the eight-bit samplers. These provide two 1 GHz baseband pairs with both right- and left-hand circular polarizations. The correlator was set up to divide each baseband into eight sub-bands each with 512 channels, resulting in a channel width of 250 kHz. This yields a velocity resolution ranging from 3.0 to 3.3 km s$^{-1}$ for the K-band and 2.0–2.7 km s$^{-1}$ for the Ka-band observations. The baseband pairs were centered at 21.8 and 24.1 GHz in K band and at 27.1 and 36.4 GHz in Ka band. They are referred to here as the 22, 24, 27, and 36 GHz basebands, respectively. These were chosen to include the metastable NH$_3$ transitions from (1, 1) with rest frequency 26.6946 GHz, to (5, 5) at 24.5330 GHz, as well as (9, 9) at 27.4779 GHz, the H$_2$O($6_{16}$–$5_{15}$) maser line at 22.2351 GHz, and the CH$_3$OH($4_{24}$–$3_{03}$) transition at 36.1693 GHz. All of the detected lines and their rest frequencies are listed in Table 1. The on-source time for the K-band and Ka-band observations was 4.4 hr and 3.6 hr, respectively. We used 3C48 as the flux density calibrator, Perley & Butler (2013), J2253+1608 as the bandpass calibrator, and J0025-2602 as the complex gain calibrator in all observations. We alternated between 10-minute intervals on NGC 253 and 1.5-minute intervals on the complex gain calibrator.

The data were reduced in the Common Astronomy Software Applications package version 4.2.2 (McMullin et al. 2007). At the adopted distance of 3.5 Mpc, the linear scale is $\approx 17$ pc per arcsecond. The half-power primary beam widths of the VLA for the K and Ka bands are 2.1 ($\sim 2$ kpc) and 1.5 ($\sim 1.5$ kpc), respectively. All data cubes were gridded with 0$''$25 pixels, mapped using natural weighting, CLEANed to $\sim 3\sigma$ rms noise, and were regridded to a common velocity resolution of 3.5 km s$^{-1}$. Continuum subtraction was performed in the UV domain. For the 24 GHz baseband, several baselines were flagged for being noisy, yielding a slightly larger synthesized beam than the 22 GHz baseband. The resulting image cubes were then smoothed to a common synthesized beam of 3$''$ × 4$''$ (position angle: 3$'$00). The common-resolution cubes are used for consistency for all the observed lines. The resulting rms noise values in the K-band and Ka-band image cubes are 0.5 mJy beam$^{-1}$ and 1 mJy beam$^{-1}$ in a 3.5 km s$^{-1}$ channel, respectively. The maser lines of H$_2$O, CH$_3$OH, and NH$_3$(3, 3) have also been imaged with 0$''$25 pixels and Briggs (robust = 0) weighting, yielding a synthesized beam of 4$''$ × 3$''$ for H$_2$O and NH$_3$(3, 3) and 2$''$ × 1$''$ for CH$_3$OH, to better constrain the locations of masing material. The rms noise in the K-band and Ka-band Briggs-weighted image cubes is 1.5 mJy beam$^{-1}$ and 3.1 mJy beam$^{-1}$ in a 3.5 km s$^{-1}$

$^5$ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
channel, respectively. A super-resolved cube was constructed for the H$_2$O maser data. This was done by deconvolving a dirty-image cube, then convolving the CLEAN components with a 1″ round beam. This super-resolved image cube was used to emphasize structures seen in the CLEAN components that are difficult to discern in the regularly resolved image cubes. No quantitative measurements were made with the super-resolved cube.

3. Results

The full continuum-subtracted spectra of our K- and Ka-band observations are presented in Figure 2. We have identified 17 transitions from seven of the different molecular or atomic species shown in Table 1. Lines were identified by searching the common-resolution data cubes with a pixel-sized beam. We set conservative conditions for a detection at a peak flux of $>1.5$ mJy beam$^{-1}$ channel$^{-1}$ for K band and $>3.0$ mJy beam$^{-1}$ channel$^{-1}$ for Ka band, and a FWHM of $\geq 30$ km s$^{-1}$ for thermal lines. For known maser transitions, single channels above 6$\sigma$ are considered detections.

3.1. Continuum Emission and RRLs

The radio continuum emission from NGC 253 is resolved in all four basebands (Figure 3). Images were made by selecting only line-free channels. The flux density measured in the 24 GHz baseband is $550 \pm 30$ mJy. This agrees with the value of $520 \pm 52$ mJy from Ott et al. (2005). The 36 GHz flux density measures $350 \pm 40$ mJy, which is in close agreement with the value of 330 mJy at 32 GHz measured by Kepley et al. (2011). The other continuum flux density measurements are $470 \pm 20$ mJy and $370 \pm 40$ mJy for the 22 and 27 GHz basebands, respectively. The spectral index derived from the K-band basebands is $-1.8 \pm 0.5$, and for Ka band, it is $0.2 \pm 0.4$. The measurements suggest that the continuum goes through a minimum between the 24 and 27 GHz basebands. The H$_{56}\alpha$ transition is the strongest RRL we detect. Figure 4 shows the relationship between the $Hubble (HST)$ H$_{\alpha}$ (Watson et al. 1996), H$_{56}\alpha$, Pa$\alpha$ (Alonso-Herrero et al. 2003), and the 36 GHz continuum emission. We treat the H$_{\alpha}$ as a tracer of the outflow with heavy dust obscuration, Pa$\alpha$ as a partially obscured star formation tracer, and RRL as an unobscured star formation tracer.
3.2. Molecular Emission Lines

Our analysis from here on focuses on NH$_3$, H$_2$O, and CH$_3$OH. These transitions are shown in boldface in Table 1. Intensity and peak flux maps are shown in Figure 5. Spectra have been extracted from the naturally weighted smoothed cubes from the pixels at the locations marked by crosses (Figure 5) and are shown in Figures 6–8. These locations were selected from the spatial peaks in the peak flux maps shown, or for spectrally unique characteristics. For example, W2 is not a spatial peak in the peak flux map, but was selected for the spectral component that is discussed in Section 3.2.2. The continuum peak is labeled C1 and identifies the starburst center. The NH$_3$ locations are labeled A1–A7. We use the NH$_3$(3, 3) line to select a representative sample of locations across NGC 253 because it is the strongest observed NH$_3$ transition. Locations for H$_2$O and CH$_3$OH are labeled W and M, respectively.

3.2.1. NH$_3$ Inversion Lines

The observed NH$_3$ emission spans an elongated structure $\sim$1 kpc in length about the continuum peak. The northeast (NE) side of the continuum peak contains three NH$_3$(3, 3) spatial peaks (A1, A2, and A3) that are blueshifted from the systemic velocity, with observed velocities ranging from $\sim$160 to 200 km s$^{-1}$. The southwest (SW) side of the continuum peak contains four NH$_3$(3, 3) peaks (A4, A5, A6, and A7) that are redshifted from the systemic velocity, with velocities ranging from $\sim$280 to 320 km s$^{-1}$. (Figure 5). The peaks A1, A2, and A3 are analogous to regions F, E, and D from Ott et al. (2005) and A4, A5, A6 and A7 are analogous to C, B, and A. It should be noted that this is not a one-to-one mapping as we have a smaller beam than the super-resolved cube used in Ott et al. (2005). The NH$_3$ spectra from each pixel are shown in Figure 6. We detect inversion transitions NH$_3$(1, 1) to (5, 5) at all locations. In addition, the NH$_3$(9, 9) line is weakly detected at site A3 (spectrum not shown). At the continuum peak all the NH$_3$ transitions are seen in absorption, with the exception of NH$_3$(3, 3). Single Gaussians were fitted to the spectrum extracted from each location, from which we extract the integrated flux, peak flux, FWHM, and the line center from the individual pixels marked in Figure 5. The properties of the metastable transitions, NH$_3$(1, 1) to (5, 5), for A1–A7 are listed.
Figure 5. Images of the NH$_3$(3, 3) (left column), H$_2$O (center column), and CH$_3$OH (right column) lines. The top row shows the peak flux images of the unsmoothed naturally weighted image cubes spanning 300 km s$^{-1}$ about the systemic velocity. The bottom row shows the intensity images smoothed to the common resolution of 6" × 4". The peak flux and intensity images are plotted with the same grayscale. The crosses mark locations where spectra were extracted for analysis, and the continuum peak is marked C1. The contour is 60 Jy beam$^{-1}$ km s$^{-1}$ of $^{12}$CO($J = 1 \rightarrow 0$) from Bolatto et al. (2013), smoothed to match the resolution of the VLA data.

Figure 6. Spectra of the NH$_3$(1, 1) to (5, 5) transitions extracted from locations A1–A7 and C1. NH$_3$(3, 3), plotted in green, show emission at all locations, whereas all the other inversion lines are absorbed toward C1. We have plotted the $^{12}$CO($J = 1 \rightarrow 0$) profile (flux density scaling factor of 0.002 and 2.5 km s$^{-1}$ resolution) from Bolatto et al. (2013) in black for comparison. The vertical dashed line denotes the systemic velocity of NGC 253 of 234 km s$^{-1}$. 
in Table 2 and C1 in Table 3. The weakly detected NH3(9, 9) fit results are listed in Table 4. We do not see the NH3 metastable inversion hyperfine transitions (J = K, ΔF = 1) as the lines are most likely weak and broad enough to be smeared out.

A1, A5, and A6 FWHMs are a few tens of km s\(^{-1}\) wider than the other locations. These three sites are located on the edges of superbubbles (see Section 4.4) discovered by Sakamoto et al. (2006). At C1, the NH3(3, 3) line appears in emission, whereas all other inversion lines appear in absorption (Figure 6), which is interpreted to be due to the existence of NH3(3, 3) masers, confirming the result from Ott et al. (2005). The NH3(3, 3) emission for C1 is not well described by a single Gaussian, and thus two Gaussians were fit to the data (Figure 9), with FWHMs of 55 ± 3 km s\(^{-1}\) and 130 ± 10 km s\(^{-1}\) and centers of 172 ± 1 km s\(^{-1}\) and 257 ± 5 km s\(^{-1}\) for NH3(3, 3)a and NH3(3, 3)b, respectively.

### 3.2.2. \(H_2O\) Masers

We identify three regions of \(H_2O\) maser emission in the data cube, labeled W1 to W3 in Figure 5 (center). The W1 water maser has been previously observed by Henkel et al. (2004) and Brunthaler et al. (2009). Spectra at these positions are

| Location | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
|----------|----|----|----|----|----|----|----|
| R.A. (J2000) h:m:ss | 00:47:34.0 | 00:47:33.6 | 00:47:33.3 | 00:47:32.8 | 00:47:32.3 | 00:47:32.2 | 00:47:31.9 |
| Decl. (J2000) \(\circ \) / \(\prime \) | −25 17 11.2 | −25 17 12.8 | −25 17 15.3 | −25 17 21.1 | −25 17 19.9 | −25 17 25.2 | −25 17 28.7 |
| Distance from C1\(\circ \) (pc) | 202 | 131 | 53 | 107 | 208 | 253 | 342 |
| \(T_{\text{Km12}}(K)\) | 99\(^{+38}_{-23}\) | 60\(^{+11}_{-4}\) | 50\(^{+11}_{-22}\) | 59\(^{+11}_{-3}\) | 68\(^{+13}_{-10}\) | 62\(^{+15}_{-10}\) | 48\(^{+9}_{-6}\) |
| \(T_{\text{Km23}}(K)\) | 107\(^{+15}_{-12}\) | 148\(^{+32}_{-11}\) | 147\(^{+34}_{-31}\) | 143\(^{+18}_{-15}\) | 154\(^{+30}_{-20}\) | 130\(^{+30}_{-20}\) | 158\(^{+31}_{-23}\) |
| \(T_{\text{Km31}}(K)\) | 229\(^{+96}_{-40}\) | 103\(^{+27}_{-13}\) | 162\(^{+24}_{-4}\) | 257\(^{+16}_{-4}\) | 145\(^{+29}_{-10}\) | 159\(^{+108}_{-48}\) | 126\(^{+27}_{-23}\) |

**Note.** \(\circ \) R.A. 00\(^{h}\)47\(^{m}\)33\(^{s}\)\(\pm\)160 decl. −25°17′17″\(\pm\)118.
shown in Figure 7. Regions W1 and W3 are seen as clear spatially resolved peaks in Figure 5. Region W1 shows multiple velocity components with the main peak labeled W1a, and the minor peaks labeled W1b and W1c. W2 is a faint feature that is not spatially resolved from W1 and W3, but marks the peak emission of a unique broad component shown in Figure 7. Regions W1 and W3 are seen as spatially more consistent with the nuclear material. This result is related to the outflow of NGC 253. W3 is a redshifted maser with a velocity of NGC 253. W2 and W3 are most likely real, given our spectral resolution, but they were not fitted by Gaussians and thus their FWHMs are upper limits.

The spectrum of W2 has contributions from W1 and W3 as they are not resolved from W2. W2 is a broad pedestal spanning ~100 km s$^{-1}$ centered at 233 km s$^{-1}$ with several narrow features. The rest of its properties are listed in Table 5. This component is much better matched to the systemic velocity of NGC 253. W3 is a redshifted maser with a single velocity component at 303 km s$^{-1}$.

W1a dominates region W1 and is blueshifted with respect to the systemic velocity, with an observed velocity of 109 km s$^{-1}$. The integrated flux density of the W1a maser is ~214 K km s$^{-1}$, yielding a luminosity of 0.66 $L_\odot$, which makes it a kilomaser. The extension is hard to discern in the peak flux maps (Figure 5), but it is clearly seen in the contours of the super-resolved image in Figure 10. 

The contours of the super-resolved image cube are plotted on the $HST$ H$\alpha$, $P$/$\alpha$, and the RRL H$S\alpha$ images. Figure 10 shows the extension perpendicular to the major axis of NGC 253. This may indicate that the W1 H$_2$O masers are related to the outflow of NGC 253, whereas W2 and W3 are spatially more consistent with the nuclear material. This result needs to be confirmed with higher resolution data. Last, we do not detect the 145 mJy km s$^{-1}$ H$_2$O maser dubbed H$_2$O-2 from Henkel et al. (2004) that was observed in 2002 September. H$_2$O masers associated with YSOs, and AGB stars can be variable on timescales of months (e.g., Claussen et al. 1996; Felli et al. 2007), therefore a non-detection is unsurprising.

### 3.2.3. 36 GHz CH$_3$OH Masers

Extragalactic 36 GHz CH$_3$OH masers were first detected by Ellingsen et al. (2014) in NGC 253 with the Australia Telescope Compact Array (ATCA)$^6$ with a $8''/0 \times 4''/2$ synthesized beam. Two sources were detected. The emission is likely not thermal in its nature, despite the large FWHM of the line, because the total integrated intensity is ~20 times greater than the total integrated intensity from the Galaxy’s central molecular zone (see Ellingsen et al. 2014). We resolve the two regions previously seen in Ellingsen et al. (2014) into five different regions with masers as marked in the peak flux map. The spectra are extracted from the common-resolution ($6''/0 \times 6''/0$) image cubes and shown in Figure 8. The pairs M1 and M2, M4 and M5 are not spatially resolved from each other in the common-resolution cube. M1 and M2 are spectrally similar, but M4 and M5 show distinct spectral components. The CH$_3$OH line is very close to the edge of one of our spectral sub-bands. There are small (3.5 km s$^{-1}$) gaps between each sub-band where the data collected are untrustworthy, thus the channel corresponding to 160 km s$^{-1}$ is lost. The data in this channel and the two adjacent channels are thus unreliable. We next fit single-component Gaussians where appropriate. The extracted properties of the lines are shown in Table 6. The region M5 was fit with two Gaussians because of the double peak. The spectral features are narrower than the NH$_3$ (this paper) and $^{12}$CO($J=1 \rightarrow 0$) features (Bolatto et al. 2013) from the same locations, with measured FWHMs ranging a range of 30–80 km s$^{-1}$. The narrower widths suggest that the 36 GHz CH$_3$OH emission does not trace the entirety of the molecular gas.

### 4. Discussion

#### 4.1. NH$_3$ Temperatures

One advantage of observing NH$_3$ is that many of its transitions are close in frequency space and therefore can be observed with a single telescope, a single observational setup, and under the same atmospheric conditions. In addition, the ~5% change in frequency between the transitions means that their respective uv coverage and the flux they resolve out are

---

$^6$ The Australia Telescope Compact Array is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.
nearly identical. Rotation temperatures can then be derived from as many pairs of metastable \((J=K)\) states as have been observed. Assuming optically thin conditions, upper level column densities may be determined from

\[
N_{JK} = \frac{\int T_{mb} dv}{\nu K^2} \exp \left( \frac{-\Delta E}{T_{mb}} \right),
\]

where the difference in energy between states \(J\) and \(J'\), \(\Delta E\), is in \(K\) (the corrected version of the equation in Henkel et al. 2000 as shown in Ott et al. 2005), and the \(g_{op}\) are statistical weights depending on the \(\text{NH}_3\) species (\(g_{op} = 1\) for para-\(\text{NH}_3\) and \(J = 3n\) where \(n\) is an integer, and \(g_{op} = 2\) for ortho-\(\text{NH}_3\) with \(J = 3n\)). Rotation temperatures derived from pairs of \(\text{NH}_3\) transitions for locations A1 to A7 are shown in Table 2. The rotation temperatures are best illustrated in the Boltzmann diagram shown in Figure 11 (top). We have plotted weighted column densities on the vertical axis and the energy above the ground state on the horizontal axis. The slopes between any two points are thus proportional to the inverse rotation temperature, i.e., cold gas shows steeper slopes than warm gas (Equation (2)). At location C1 we see \(\text{NH}_3\) in absorption.
against the continuum (Figure 6) and thus the rotation temperature must be measured differently (see next paragraph). A3 is located ~0.5 beams (53 pc) from C1, thus the emission line is most likely partially absorbed, making rotation temperature measurements here unreliable.

Measuring rotation temperatures from NH$_3$ absorption is not possible without knowing the excitation temperature $T_{ex}$ and the optical depth $\tau$. Huettemeister et al. (1995) describes the process of extracting total NH$_3$ column densities $N_{JK}$ (the sum of both the upper and lower inversion states):

$$N_{JK} = 1.61 \times 10^{14} \frac{J(J + 1)}{K^2} \tau \Delta v_{1/2},$$

and

$$\tau = -\ln \left(1 - \frac{|T_L|}{T_C}\right),$$

where the units of $\Delta v_{1/2}$(FWHM) are km s$^{-1}$, $T_L$ and $T_C$ are brightness temperatures of the line and continuum, respectively, and $\tau$ is the optical depth. We have no means to measure the transition-dependent excitation temperature, so for simplicity we assume that for each metastable transition $T_{ex}$ is equal. In this case, the rotation temperature can still be derived from Equation (2) by substituting $N(J, K)$ for $N_0(J, K)$. Rotation temperatures for C1 are shown in Table 3. Since the column density at C1 depends on the excitation temperature, the values plotted for C1 in Figure 11 are really $N(J, K)/T_{ex}$. The spatial dependence of the rotation temperature is shown in Figure 11 (bottom).

The rotational temperature is not necessarily the true thermal temperature of the gas, i.e., it is not the kinetic temperature, but rather a lower limit. We therefore employ the functions from Ott et al. (2011) to estimate kinetic temperatures. To convert rotation temperatures for the NH$_3$(2, 2) into (4, 4) ratio, additional fits to the same large velocity gradient (LVG) models used in Ott et al. (2011) from Ott et al. (2005) were made:

$$T_{Kin} = \begin{cases} 1.467 \times T_{24} - 6.984 & \text{for } T_{Kin} \lesssim 100 \text{ K} \\ 27.085 \times \exp(0.019 T_{24}) & \text{for } T_{Kin} \gtrsim 100 \text{ K} \end{cases}$$

and for the NH$_3$(4, 4) to (5, 5) ratio:

$$T_{Kin} = \begin{cases} 1.143 \times T_{45} - 1.611 & \text{for } T_{Kin} \lesssim 50 \text{ K} \\ 21.024 \times \exp(0.0198 T_{45}) & \text{for } T_{Kin} \gtrsim 50 \text{ K} \end{cases}$$

Figure 12 shows how the conversion functions fit to the LVG models. We thus derive kinetic temperatures for adjacent pairs of like species for a total of three measurements at each location (Table 2).

If the gas is dominated by a single kinetic temperature, all the rotation temperatures should yield this temperature. When the rotation temperatures fail to do this, the gas must either be represented by multiple kinetic temperatures, or the LVG approximation does not hold. The LVG corrected kinetic temperatures are plotted in Figure 13. The figures show remarkably little variance in the rotation and kinetic temperatures measured across all locations. We fit a single temperature for each line pair across all locations weighted by the errors. We measure a weighted average for $T_{Kin24}$ of 57 $\pm$ 4 K, for $T_{Kin45}$ of 134 $\pm$ 8 K, and for $T_{Kin55}$ of 117 $\pm$ 16 K. The $T_{Kin24}$...
and $T_{\text{Kin5}}$ components are consistent within the errors. The kinetic temperatures of the dense molecular gas in the central kpc of NGC 253 are therefore most consistent with a cool $\sim$57 K derived from the (1, 1) and (2, 2) lines, and a warm $\sim$130 K component derived from the weighted average of the (2, 2) to (4, 4) and (4, 4) to (5, 5) ratios.

The NH$_3$ transitions of NGC 253 have been of interest to many others, but most recently, they have been observed with the ATCA (Ott et al. 2005), the VLA (Takano et al. 2005), and the Green Bank Telescope (GBT) (Mangum et al. 2013). Using interferometric observations of the bar, Ott et al. (2005) measure rotation temperatures $T_{12} \sim 42$ K, and Takano et al. (2005) measure $T_{12} \sim 26$ K. The lower temperature measured in Takano et al. (2005) is most likely due to a low signal-to-noise ratio for the NH$_3$(2, 2) line. Unlike what Ott et al. (2005) found, we see that a single temperature does not describe the dense molecular gas in NGC 253. Ott et al. (2005) observe the (1, 1), (2, 2), (3, 3), and (6, 6) lines, while our analysis, which includes the NH$_3$(4, 4) and (5, 5) lines, clearly indicates a warm component that was not observed by Takano et al. (2005) and a cooler component that was not observed by Ott et al. (2005). Mangum et al. (2013) indicated that there is a warm component to the dense molecular gas in NGC 253 because their analysis included the NH$_3$(4, 4) line, but it is limited by the 30" beam of the GBT. This limits their analysis to the NW and SE velocity components, measuring $T_{\text{Kin24}}$ of $73 \pm 22$ K and $<150$ K, respectively. It is possible that these measurements are affected by absorption in the center of NGC 253 or that they are sensitive to a more diffuse component of the molecular gas. On average, they measure a kinetic temperature of $78 \pm 22$ K from the NH$_3$(J, $K \leq 4$) transitions for the whole galaxy, which is broadly consistent with the results presented in this paper. Modeling of the CO ladder from $J = 4$–3 to $J = 13$–12 from Rosenberg et al. (2014) yields similar results. They find evidence for three temperature and density components for the molecular ISM ranging from 60 K to 110 K and $10^{15.5}$ cm$^{-3}$ to $10^{15.5}$ cm$^{-3}$, respectively. Their observations from the Herschel Space Observatory have a resolution of 32".5. Our NH$_3$ analysis does not reveal any information about the density of the molecular gas. Therefore our results are only broadly consistent in terms of temperature analysis.

The spatially uniform distribution of the temperatures is perhaps surprising because of the concentration of supernovae remnants in the central 500 pc (Ulvestad & Antonucci 1997). We would expect that if heating by supernovae were a dominant effect in setting the state of a GMC, then an increase in temperature toward the center of the bar would be observed as the density of supernovae increases toward the center of NGC 253. This may not be true during the bulk of a

### Table 6

| R.A.(J2000) | Decl.(J2000) | Velocity Component | $T_{\text{mb}}$ (K km s$^{-1}$) | $V_{\text{LSR}}$ (km s$^{-1}$) | $V_{\text{FWHM}}$ (km s$^{-1}$) | $T_{\text{mb}}$ (K) | Luminosity $L_{\odot}$ |
|------------|-------------|-------------------|-----------------------------|-----------------------------|-------------------|-----------------|----------------|
| 00:47:34.1 | −25 17 11.7 | M1                | 1.38 ± 0.07                 | 202.0 ± 0.3                 | 49.2 ± 3.1        | 0.026 ± 0.005  | 0.63            |
| 00:47:33.9 | −25 17 10.8 | M2                | 1.41 ± 0.07                 | 195.4 ± 0.8                 | 32.2 ± 2.3        | 0.040 ± 0.006  | 0.65            |
| 00:47:33.7 | −25 17 13.1 | M3                | 3.59 ± 0.14                 | 165.9 ± 1.7                 | 85.8 ± 4.4        | 0.039 ± 0.008  | 1.63            |
| 00:47:31.9 | −25 17 25.7 | M4                | 3.09 ± 0.18                 | 294.1 ± 2.6                 | 84.3 ± 5.6        | 0.035 ± 0.005  | 1.42            |
| 00:47:32.0 | −25 17 28.9 | M5                | a 2.19 ± 0.89               | 294.3 ± 3.0                 | 35.7 ± 4.8        | 0.056 ± 0.005  | 1.01            |
|            |             |                   | b 2.33 ± 0.96               | 331.6 ± 10.2                | 54.5 ± 16.9       | 0.041 ± 0.005  | 1.06            |

### Table 7

| Location  | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
|-----------|----|----|----|----|----|----|----|
| NH$_3$(1, 1)/NH$_3$(2, 2) | $T_{\text{Kin}}$ (K) | 117 ± 135 | 69 ± 24 | 54 ± 27 | 69 ± 24 | 81 ± 41 | 72 ± 27 | 57 ± 18 |
| NH$_3$(2, 2)/NH$_3$(4, 4) | $T_{\text{Kin}}$ (K) | 111 ± 24 | 156 ± 39 | 165 ± 75 | 150 ± 33 | 165 ± 48 | 108 ± 24 | 162 ± 42 |

**Note.** Median temperatures of the best-fit LVG model to the data. The uncertainty on the kinetic temperature fit is asymmetric, therefore the uncertainty reported here is the greater 1σ deviation from the best fit.

---

**The Astrophysical Journal, 842:124 (21pp), 2017 June 20**

Gorski et al.
shown with a vertical dashed line. All the para species of NH₃ appear in absorption, while the NH₃ represents the best-para-NH₃ species. The results are tabulated in Table 7 and qualitatively displayed in Figure 14. In the region of greatest energy input, heating may also not be observed because supernovae might dissociate NH₃ molecules altogether in the region of greatest energy input.

4.2. LVG Fitting with RADEX

To further investigate the need for multiple temperatures, we attempt to directly fit the data with LVG models. We do this to compare the results with the approximation to the LVG correction in Section 4.1. We use RADEX (Van der Tak et al. 2007) with collisional coefficients from the LAMBDA database (Schöier et al. 2005). RADEX was not used by Ott et al. (2005, 2011), but it does make use of some of the same collisional coefficients. The collisional coefficients from the LAMBDA database cover temperatures of up to 300 K, thus the kinetic temperature axis of the grid spans 0–300 K in steps of 3 K. The collider (H₂) volume density and NH₃ column density axes of the grid are logarithmically sampled from 10⁻² to 10⁶ cm⁻³, respectively, and from 10¹³ and 10¹⁷ cm⁻² with 100 steps each. In the LVG approximation the ratio N/Δν is the independent variable, but in RADEX the column density and line width are specified separately. We specify a line width calculated from the weighted mean of 74 km s⁻¹ from all the para species of NH₃ in Table 2.

The fits were carried out for each ratio of adjacent J = K para-NH₃ species. The results are tabulated in Table 7 and qualitatively displayed in Figure 14. In the figure the median fitted temperature is drawn with a dashed line between the 1σ confidence contours. The errors are calculated from the rms of the median fit for values above a critical density of ~10³ cm⁻³, see Cheung et al. (1968). Below this density there is a slight upturn to the temperature parameter, suggesting that high T and low n may excite ammonia at relatively low densities. This high-T low-n condition is unlikely as many higher critical density gas tracers have been observed to have a similar structure in the nucleus of NGC 253, see Meier et al. (2015). The H₂ density is not well constrained, with error bars that span the entirety of the sampled parameter space, which is consistent with NH₃ not being a density probe. Generally, the fits are well behaved, with the exception of the (4, 4) to (5, 5) ratio (not shown), for which the best-fit solutions are poorly constrained and tend toward the edge of the temperature axis, with values of ~300 K. It is possible that there is a component that is hotter than our temperature range allows, but we cannot provide any meaningful estimates from the fitting. In contrast to the (4, 4) to (5, 5) ratio, the (1, 1) to (2, 2) and (2, 2) to (4, 4) ratios are well behaved. The solutions cover two regions of parameter space indicating a warm and cool component (Table 7). The spatial distribution of temperatures is mostly uniform for the cool component, derived from line ratios NH₃(1, 1)/NH₃(2, 2), with an average temperature of 74 ± 12 K, and likewise for the warm component, derived from the NH₃(2, 2)/NH₃(4, 4) ratio, with an average temperature of 145 ± 14 K. This is broadly consistent with the analysis in Section 4.1.

4.3. Nature of the 36 GHz CH₃OH Masers

The nature of the 36 GHz methanol masers appears different from what we understand of their Galactic counterparts. Yusef-Zadeh et al. (2013) performed a CH₃OH maser survey of the inner 160 × 43 pc of the Galaxy. We use their study as a template to address CH₃OH emission in NGC 253. The CH₃OH line widths in NGC 253 span tens of km s⁻¹, whereas individual Galactic CH₃OH masers tend to span a few km s⁻¹. The NGC 253 36 GHz line is spectrally resolved and multiple components can be fitted (see Table 6). The maser with the highest flux found by Yusef-Zadeh et al. (2013) (number 164) is ~470 Jy km s⁻¹, which corresponds to an isotropic luminosity, assuming a distance of 8 kpc, of 1.1 × 10⁻³ L☉. By comparison, the most luminous CH₃OH maser in NGC 253 is 1.63 L☉. This would mean that the beam-averaged Class I CH₃OH masers in NGC 253 are about a thousand times more luminous than the most luminous CH₃OH maser found by Yusef-Zadeh et al. (2013). Alternatively, there may be thousands of bright masers at similar velocities in one 6″ × 4″ beam. Surveys of Class I methanol masers in supernovae remnants (e.g., McEwen et al. 2014 & McBreen et al. 2016) have revealed spectrally similar results to Yusef-Zadeh et al. (2013), with narrow spectral features spanning a few km s⁻¹. At our spatial resolution of 101 × 67 pc, the CH₃OH emission is not well resolved, and the entirety of the Yusef-Zadeh et al. (2013) survey corresponds approximately to the size of one of our beams. Since there are >300 sources in a similar region of the Galaxy and the NGC 253 spectra show multiple velocity components, it is possible that there are many components at each location. The broad spectral profile could be constructed from many masers from protostellar outflows or supernovae remnants.
4.4. Impact of Superbubbles on the Dense Molecular ISM

Sakamoto et al. (2006) find two superbubbles in NGC 253 in the $^{12}$CO ($J = 2 \rightarrow 1$) emission. The shells are ~100 pc in diameter, have masses on the order of $10^6 M_\odot$, and kinetic energies on the order of $10^{46}$ J, suggesting winds and supernovae from a superstar cluster, or a hypernova, as the creation mechanism. Close to the location where these superbubbles interact with dense molecular gas, as traced by NH$_3$, we observe CH$_3$OH masers. Figure 15 shows $^{12}$CO ($J = 1 \rightarrow 0$) channel maps of the superbubbles with CH$_3$OH contours overlaid. There are two groups of masers. The first is on the NE side of the galaxy and consists of M1, M2, and M3. The other group consists of M4 and M5 on the SW side (Figure 5). All the CH$_3$OH masers except for M3 can be associated with the Sakamoto superbubbles. The association indicates that these masers exist where clouds are influenced by the expanding superbubbles. This relationship is also indicated by larger NH$_3$ line widths at the locations A1, A5, and A6, which are nearest the masers and the superbubbles.

The larger observed line widths are probably not a result of more turbulence within the clouds. A comparison with the GMCs from Leroy et al. (2015) suggests that the broader observed line widths in our data are most likely a result of beam-smearing effects. With a 2″ beam, Leroy et al. (2015) are able to resolve individual clouds. Their clouds are clearly dominated by turbulence, as in all cases the thermal line width is <1 km s$^{-1}$, as calculated from our NH$_3$ derived temperatures. Using an average temperature of 117 K derived from our NH$_3$ analysis, the mean thermal energy stored in the Leroy et al. (2015) clouds is $\sim 5 \times 10^{43}$ J, whereas the mechanical energy stored, as derived from turbulent line widths, is $\sim 1 \times 10^{46}$ J. The turbulent line widths of individual GMCs detected in Leroy et al. (2015) appear unaffected by the impact of the expanding superbubbles, and in fact appear uniform across the entire central molecular bar (Figure 16). The larger NH$_3$ line widths observed with a larger beam suggest instead that the superbubbles are imparting mechanical energy, which results in bulk translational motion of the GMCs.

The relationship of the clouds to the masers is shown in Figure 17, which plots kinetic temperatures $T_{\text{kin,12}}$ and $T_{\text{kin,24}}$ derived from NH$_3$ against the mean FWHM of the NH$_3$ transitions. The figure shows little temperature variation toward the shocks traced by CH$_3$OH. If there is shock heating of the dense molecular gas, it must be highly localized to areas much smaller than the beam such that it does not affect the overall kinetic temperature measured with ~100 pc spatial resolution.

4.5. The Outflow, Masers, and Starburst

4.5.1. NH$_3$(3, 3) Masers

The location of the continuum peak (C1) is also the locus of the starburst and the central base of the molecular and ionized
bipolar outflow. Here the para-NH$_3$ lines are not observed in emission, but the ortho-NH$_3$(3, 3) line is. We did not detect any other ortho species of NH$_3$ at this location to compare with these lines, but Ott et al. (2005) did observe the ortho (6, 6) species to be in absorption at our location C1. Since NH$_3$(3, 3) is the only ortho-NH$_3$ species observed in emission at this location, we corroborate the interpretation from Ott et al. (2005) that the NH$_3$(3, 3) line is masing here. The spectral line (Figure 6) could not be fit with a single Gaussian, but rather two Gaussians centered at 172 km s$^{-1}$ and 257 km s$^{-1}$ with widths of 55 km s$^{-1}$ and 130 km s$^{-1}$, respectively, NH$_3$(3, 3)a and NH$_3$(3, 3)b (see Figure 9). The existence of the NH$_3$(3, 3) maser suggests that the collision rate in the center of NGC 253 increases or that there exists an excess of infrared photons in the center in order to pump this maser. Currently, there is one other known extragalactic source of NH$_3$(3, 3) masers in addition to NGC 253: the Seyfert galaxy NGC 3079 (Miyamoto et al. 2015). Both galaxies host outflows, but NGC 3079 is host to an active galactic nucleus (AGN). It hosts an SFR of 2.6 $M_{\odot}$ yr$^{-1}$ over 4 kpc (Yamagishi et al. 2010) measured from 1 to 1000 $\mu$m emission. Attribution to an AGN driven wind might be favored because the starburst is weak. Since the mechanism driving the outflows in these galaxies is different, we hypothesize that in both cases it is the collision of the hot ionized outflow cone with the surrounding material that results in the NH$_3$(3, 3) masers.

4.5.2. H$_2$O Masers

The H$_2$O masers are located within the centermost 200 pc. Because they are located at the center of the starburst, it is likely that all these masers are related to star formation. Brunthaler et al. (2009) investigated this location with the VLBA and inferred a pure starburst nature of the masers based on their similarity to Galactic H$_2$O masers and spatial coincidence with supernovae remnants. Our data, while much lower in resolution, indicate that W1 may be extended perpendicular to the disk and aligned with the bipolar ionized gas outflow (Figure 10). The spectrum shows evidence of multiple components (Figure 7). W2 contains many individual components within a velocity space $\sim$100 km s$^{-1}$ wide that is centered at the systemic velocity and includes contributions from W1 and W3. W3 is a single-component maser located to the SW of the nucleus.

W3 is the simplest H$_2$O maser to explain. It is cospatial with an H II region seen in Figure 4 and has a narrow spectrum. It is likely associated with a massive star or stars in that region. Its isotropic luminosity of $2 \times 10^{-2}$ $L_{\odot}$, is consistent with luminosities of AGB and YSO H$_2$O masers in the Galaxy (e.g., Palagi et al. 1993).

The H$_2$O maser W1 is the clear oddity in NGC 253. W1 is most clearly seen in the super-resolved image in Figure 10. There are three components with observed velocities in the range 25–109 km s$^{-1}$, while the systemic velocity of the galaxy is 234 km s$^{-1}$. The W1 maser emission does not follow the kinematics of the dense molecular ISM (Figure 7). The most luminous and broad component is centered at 109 km s$^{-1}$. According to Brunthaler et al. (2009), this maser emission is associated with supernova remnant TH4 (Turner & Ho 1985 and Ulvestad & Antonucci 1997). However, because of the extreme conditions under which H$_2$O is known to mase, in addition to the locations and velocities, and because no H$_2$O masers are found in Milky Way supernova remnants (Claussen et al. 1999 and Caswell et al. 2011), we hypothesize that these masers are tracing shocks in entrained material in the outflow.

We consider three possibilities for the origin of the masers. First, Figure 11 in Strickland et al. (2002) shows possible anatomies of starburst-driven outflows in NGC 253. In this picture the W1 H$_2$O masers most likely trace dense-gas clumps closest to the starburst center or shocked dense gas entrained in the outflow. The observed velocities are consistent with the Strickland model predictions for outflow velocities on the order of 100 km s$^{-1}$. A model of a conical outflow developed by analyzing optical integral field unit data in
Westmoquette et al. (2011) presents a more direct view of the outflow associated with the base of the outflow is blueshifted $\sim$100 ± 50 km s$^{-1}$ with respect to systemic. This is a good match to the observed velocities of W1a to W1c, suggesting that there are shocks related to the outflow. The origin of the shocks remains unknown as we do not see a spatial separation of W1a, b, and c, even in the super-resolved image cube. We hypothesize that they may be shocks in entrained material in the outflow, or collisions with dense gas that funnels the outflow out of the galactic plane. In this picture W2 does not have observed velocities that match either the Strickland et al. (2002) or Westmoquette et al. (2011) models of the outflow. The velocity center of W2 matches the systemic velocity of NGC 253, suggesting that it may exist in a molecular torus about the center. The velocities of the NH$_3$(3, 3) masers and the $^{12}$CO($J = 1 \rightarrow 0$) spectrum from the same location are similar (Figure 7). In the Strickland models the NH$_3$(3, 3) and W2 H$_2$O masers would exist where the outflow impacts the unperturbed disk, which triggers star formation. The W2 H$_2$O narrow components are most likely generated by YSOs in the nuclear starburst, and the NH$_3$ masers, they are probably star-forming sites like that of DR 21 (Wilson & Mauersberger 1990) or W51 (Godd et al. 2015) in the Galaxy.

The second possibility is that while the W1 masers still originate in the outflow, the W2 masers do not trace a molecular torus, but their velocity extent is instead due to a two-sided outflow. Here the portion of W2 that is redshifted with respect to the systemic velocity is tracing the receding side of the outflow. However, the receding side is not as well understood because it is obscured by dust and tipped away from the observer, making optical and soft X-ray observations difficult. Westmoquette et al. (2011) find it impossible to model the receding outflow cone, and the analysis from Strickland et al. (2002) is focused on kpc scales. Therefore current evidence for the receding outflow is limited to hundreds of pc displacement from the disk. As H$_2$O masers are unaffected by dust obscuration, this picture implies fewer shocked regions as traced by H$_2$O on the receding side of the outflow, or that other masers in the receding outflow are unobserved because of line-of-sight effects. In this case the W1 masers would exist as in the first picture.

Last, it is possible that the W1 H$_2$O masers are not related to the outflow at all, leaving us with the difficulty of explaining their velocities. Brunthaler et al. (2009) noted that W1 is cospatial with the supernova remnant TH4. The W2 masers in this case would most likely be gas in the molecular torus as in the first picture or associated with known supernova remnants at their location. With an rms of 12 mJy, it is unlikely that Brunthaler et al. (2009) would have seen the fainter masers comprising W2. Our spatial resolution makes this problem difficult to solve, thus deeper high-resolution observations are necessary.

4.6. Millimeter Molecular Lines

In order to reveal the underlying properties responsible for the observed temperatures and masers, we compare our results with images of several molecular species from Meier et al. (2015), who observed NGC 253 with ALMA in the millimeter range. We have chosen five molecules that trace PDRs (113.40 GHz CN(1-0); 1/2–1/2), see Rodriguez-Franco et al. 1998), intermediate densities (89.18 GHz HCO$^+$ (1-0)) found in both diffuse and dense clouds (Turner 1995), gas densities greater than $3 \times 10^3$ cm$^{-3}$ (88.63 GHz HCN (1-0), see Gao & Solomon 2004), weak shocks (89.92 GHz HNCO (4$_{0,4}$–$3_{0,3}$, see Meier & Turner 2005), and strong shocks.
Figure 15. Channel maps of the regions containing the superbubbles found by Sakamoto et al. (2006). The top block shows the eastern superbubble (R.A.: 00h47m34.64, decl.: −25°17′09.5″), and the bottom block shows the western superbubble (R.A.: 00h47m32.53, decl.: −25°17′24.0″). Each box is 18″ × 18″. The black circle shows the diameter of the superbubbles measured by Sakamoto et al. (2006). The grayscale image shown is $^{13}$CO($J = 1 \rightarrow 0$) emission from Bolatto et al. (2013). The contours of 1, 2, 3, and 5 times the 4.5 mJy beam$^{-1}$ of CH$_3$OH are shown, and the velocity in km s$^{-1}$ is shown in the top right corner of each panel.
The largest spatial scale in the sample examined by Meier et al. (2015) is 18″. They compare the ALMA interferometric maps with single-dish observations and find that 50%–100% of the total flux is recovered. The largest spatial scale of the VLA D configuration at K band is 66″, thus we expect less flux to be resolved out by the VLA than for ALMA. The maximum uncertainty in the line ratios of the VLA to ALMA could consequently be increased by a factor of two. The resolution of the ALMA cubes is \( \sim 2″ \times 2″ \). The HCN map, with NH$_3$(3, 3) contours in white, is shown in Figure 18. The two molecular morphologies are well correlated. This suggests that these molecules are tracing similar environments. We show the PDR and dense gas tracers, CN and HCO$^+$, with NH$_3$(3, 3) contours overlaid (Figure 19 top). Like HCN, CN and HCO$^+$ trace similar regions as NH$_3$.

For the shock tracers, HNCO and SiO, we have overplotted the naturally weighted unsmoothed 36 GHz CH$_3$OH contours (Figure 19 bottom). The CH$_3$OH masers are well correlated with HNCO and SiO at the sites of the Sakamoto et al. (2006) superbubbles, but the centermost 200 pc remains bright in SiO, whereas HNCO dims (Meier et al. 2015). The CH$_3$OH masers appear much better correlated with HNCO than SiO. We take the dominant source of error in the individual molecular maps to be the 10% estimate in the absolute flux density calibration. To estimate relative intensities, the individual ALMA maps were smoothed to the common resolution of 6″ × 4″ to match our VLA data. We then normalized these maps by the HCN map. Line ratios were then measured at locations A1–A7 and C1. The line ratios are shown in Figure 20 plotted in black, with the $T_{\text{Kin}24}$ shown in red and $T_{\text{Kin}12}$ shown in blue.

The cold and warm temperature components of the molecular gas do not correlate well with PDR tracers (CN), intermediate densities (HCO$^+$), weak shocks (HNCO), or strong shocks (SiO). We interpret the plots in Figure 20 to mean that none of the selected processes relate to the heating and cooling of the dense molecular ISM on 100 pc scales in NGC 253. This possibly means that cosmic rays are the dominant source of heating in the center of NGC 253, or that the dominant heating source destroys NH$_3$ molecules and we are only sensitive to less impacted molecular gas.

At the same time, we measure a relative decrement of HNCO in the center compared to the locations with 36 GHz CH$_3$OH masers and the expanding Sakamoto et al. (2011) superbubbles. In the case of NGC 253, Meier et al. (2015) argue that the
relative decrement of HNCO is a consequence of dissociation in the PDR-dominated center. The lack of methanol masers on the eastern side of the west superbubble is consistent with dissociation closer to the center. It is interesting that the nonthermal 36 GHz CH$_3$OH correlates with the HNCO. A similarly tight correlation has been observed between HNCO and thermal CH$_3$OH in nuclei (e.g., Meier & Turner 2005, 2012). This is further evidence that the 36 GHz CH$_3$OH is tracing similar shocked regions. SiO is also enhanced near the superbubbles. However, SiO is more uniformly distributed in the center 300 pc of NGC 253 where we did not observe any 36 GHz CH$_3$OH masers, suggesting that the 36 GHz CH$_3$OH maser is more closely related to weak shocks than to strong shocks. Position-velocity (PV) cuts were made through the eastern and western groups of masers. Figure 21 shows the PV cuts through the HCN cube with the naturally weighted 36 GHz methanol contours in black. The HCN cube reveals a few shell-like structures. The methanol masers are well correlated with the edges of the shells, which strengthens the connection between the shocks and the dense molecular gas.

5. Summary

We have provided an analysis of VLA observations of the dense gas and masers associated with the nuclear starburst in NGC 253. We conclude the following:

1. We have detected NH$_3$(1, 1), (2, 2), (3, 3), (4, 4), and (5, 5) in the central kpc of NGC 253. NH$_3$(9, 9) is detected in only one location. No NH$_3$ is observed in the molecular outflow.

2. We find that the molecular gas in NGC 253 is best described by a spatially uniform two kinetic temperature model with a warm 130 K component and a cool 57 K component. The continuum peak (C1) may indeed be hotter as it is closer to the starburst, but absorption of the metastable para-NH$_3$ lines makes the temperature measurements less accurate. A direct LVG analysis...
 corroborates a two-temperature model of NGC 253, although with a cool component of 74 K and a warm component of 145 K. The LVG analysis does hint at a hotter component greater than 300 K as traced by the NH$_{3}$(4, 4) and NH$_{3}$(5, 5) ratio. The temperature distribution is not well correlated with PDRs, weak shocks, or strong shocks, and is constant over the central kpc.

3. We confirm the result from Ott et al. (2005), who suggested that NH$_{3}$(3, 3) masers exist in the nucleus of NGC 253. There is currently only one other known source of extragalactic NH$_{3}$(3, 3) masers, NGC 3079 (Miyamoto et al. 2015). Both galaxies host outflows, but in NGC 253 the outflow is driven by a starburst, whereas in NGC 3079 it is most likely driven by an AGN.

4. Expanding superbubbles do not appear to heat the gas in NGC 253. A comparison with the results from Leroy et al. (2015) shows that the line widths are dominated by turbulent motions within a GMC. The large NH$_{3}$ line widths are likely due to the bulk motion of the GMCs.

5. Three H$_{2}$O maser features have been observed. The H$_{2}$O maser W1 is coincident with the continuum peak. The H$_{2}$O masers show indications that emission is extended along the minor axis of the galaxy, the spectrum suggests multiple components, and the velocities are more similar to the outflow than the disk. It is likely that this maser is related to the bipolar outflow of ionized gas, although other explanations are possible. High-resolution follow-up observations are needed to confirm a relationship with the bipolar outflow.

W2 is located SW of W1 and shows multiple spectrally unresolved masers with velocities centered about the systemic velocity, suggesting that these masers exist in a circumnuclear torus. It is also possible that W2 may in part trace the receding side of the outflow. W3 is unresolved and located SW of W1 and W2. Its progenitor is most likely a massive star.

6. We detect five regions with 36 GHz CH$_{3}$OH masers at the outside edge of the central kpc as traced by NH$_{3}$. The spatial proximity and velocities suggest a relationship with known superbubbles. Position-velocity cuts show that all the 36 GHz methanol masers may be related to shell-like features. The 36 GHz CH$_{3}$OH morphology and HNCO are similar. This similarity suggests that both HNCO and 36 GHz methanol masers are tracing similar conditions.

Our analysis reveals the properties of the dense molecular ISM along the central kpc of NGC 253 using centimeter and millimeter emission and absorption lines. We have uncovered relationships with the bipolar outflow, expanding molecular bubbles, and the nuclear starburst.

Mark Gorski acknowledges support from the National Radio Astronomy Observatory in the form of a graduate student.
internship, and a Reber Fellowship. We would like to thank Alberto Bolatto and Adam Leroy for sharing the ALMA image cubes. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is maintained by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration (NASA) and NASA’s Astrophysical Data System Abstract Service (ADS).

References
Alonso-Herrero, A., Rieke, G. H., Rieke, M. J., & Kelly, D. M. 2003, AJ, 125, 1210
Bolatto, A. D., Warren, S. R., Leroy, A. K., et al. 2013, Natur, 499, 450
Brunthaler, A., Castangia, P., Tarchi, A., et al. 2009, A&A, 497, 103
Caswell, J. L., Breen, S. L., & Ellingsen, S. P. 2011, MNRAS, 410, 1283
Cheung, A. C., Rank, D. M., Townes, C. H., Thornton, D. D., & Welch, W. J. 1968, PhRvL, 21, 1701
Claussen, M. J., Goss, W. M., Frail, D. A., & Seta, M. 1999, AJ, 117, 1387
Claussen, M. J., Wilking, B. A., Benson, P. J., et al. 1996, ApJS, 106, 111
Crain, R. A., Schaye, J., Bower, R. G., et al. 2015, MNRAS, 450, 1937
Dale, D. A., Cohen, S. A., Johnson, L. C., et al. 2009, ApJ, 703, 517
Ellingsen, S. P., Chen, X., Qiao, H.-H., et al. 2014, ApJL, 790, L28
Ellingsen, S. P., Sobolev, A. M., Cragg, D. M., & Godfrey, P. D. 2012, ApJL, 759, L5
Felli, M., Brand, J., Cesaroni, R., et al. 2007, A&A, 476, 373
Fuente, A., Martín-Pintado, J., Cernicharo, J., & Bachiller, R. 1993, A&A, 276, 473
Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271
García-Burillo, S., Martín-Pintado, J., Fuente, A., & Neri, R. 2000, A&A, 355, 499
Goddi, C., Henkel, C., Zhang, Q., Zapata, L., & Wilson, T. L. 2015, A&A, 573, A109
Goddi, C., & Moscadelli, L. 2006, A&A, 447, 577
Haas, M. R., Schaye, J., Booth, C. M., et al. 2013, MNRAS, 435, 2931
Hartmann, L., Ballesteros-Paredes, J., & Bergin, E. A. 2001, ApJ, 562, 852
Henkel, C., Mauersberger, R., Peck, A. B., Falcke, H., & Hagiwara, Y. 2000, A&A, 361, L45
Henkel, C., Tarchi, A., Menten, K. M., & Peck, A. B. 2004, A&A, 414, 117
Ho, P. T. P., & Townes, C. H. 1983, ARA&A, 21, 239
Hopkins, P. F., Kereš, D., Ohsoro, J., et al. 2014, MNRAS, 445, 581
Hopkins, P. F., Quataert, E., & Murray, N. 2011, MNRAS, 417, 950
Hopkins, P. F., Quataert, E., & Murray, N. 2012, MNRAS, 421, 3488

Figure 21. Position-velocity (PV) cuts through the HCN (grayscale) and 36 GHz methanol maser (3, 6, and 9σ contours shown in black) data cubes. The PV cuts show a few shell-like structures marked with black circles. The methanol masers appear to be concentrated around the edges of the shells.
