THE TEMPERATURE DISTRIBUTION OF DENSE MOLECULAR GAS IN THE CENTER OF NGC 253

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Received 2005 January 12; accepted 2005 May 4

ABSTRACT

We present interferometric maps of ammonia (NH$_3$) of the nearby starburst galaxy NGC 253. The observations have been taken with the Australia Telescope Compact Array and include the para-NH$_3$ (1, 1) and (2, 2) and the ortho-NH$_3$ (3, 3) and (6, 6) inversion lines. Six major complexes of dense ammonia are identified, three of them on either side of the starburst center, out to projected galactocentric radii of $\sim$250 pc. Rotational temperatures are derived toward selected individual positions, as well as for the entire southeastern and northwestern molecular complexes. The application of radiative transfer large velocity gradient models reveals that the bulk of the ammonia molecules is embedded in a one-temperature gas phase. Kinetic temperatures of this gas are $\sim$200 and 140 K toward the southwest and northeast, respectively. The temperatures under which ammonia was formed in the past are with $\geq$30 K also warmer toward the southwest than toward the northeast ($\sim$15–20 K). This is indicated by the ortho-ammonia–to–para-ammonia ratio, which is $\sim$1 and 1.5–2.5 toward the southwest and northeast, respectively. Ammonia column densities in the brightest complexes are in the range of $(6-11) \times 10^{14}$ cm$^{-2}$, which adds up to a total ammonia mass of $\sim$20 $M_\odot$, about evenly distributed toward both sides of the nucleus. Ammonia abundances relative to H$_2$ are $\sim 3 \times 10^{-8}$. In the southeastern complex, the ammonia abundances increase from the starburst center to larger galactocentric radii. Toward the center of NGC 253, NH$_3$ (1, 1), (2, 2), and (6, 6) are detected in absorption against an unresolved continuum source. At the same location, however, ammonia (3, 3) is found in emission, which indicates maser activity. This would be the first detected extragalactic NH$_3$ maser. Evidence for an expanding shell in the southwestern complex is provided. The shell, with a dynamical age of $\sim$1.3 Myr, is centered on an X-ray point source that must be located within the dense gas of NGC 253. The shell and X-ray properties can be reproduced by the energy input of a highly obscured young stellar cluster with a mass of $\sim$10$^5$ $M_\odot$, which also heats the dense gas. A current star formation rate of $\sim$2.8 $M_\odot$ yr$^{-1}$ is derived for the nuclear starburst in NGC 253 based on its 1.2 cm continuum emission.

Subject headings: galaxies: individual (NGC 253) — galaxies: ISM — galaxies: nuclei — galaxies: starburst — ISM: molecules — radio lines: galaxies

1. INTRODUCTION

Starburst galaxies are a main contributor to the star formation (SF) in the universe ($\sim$20% at $z < 0.2$; Brinchmann et al. 2004). The fuel for star formation is dense molecular gas. Recently Gao & Solomon (2004) showed that in actively star-forming galaxies the molecular gas with volume densities $>10^4$ cm$^{-3}$ (traced by HCN) correlates very well with the SF rate (SFR) determined by the far-infrared (FIR) emission. Less dense molecular gas, such as that traced by CO, is a weaker measure of the current SFR. The physical state of the molecular gas is mainly described by its temperature and density. It is thus important to constrain the range of those two fundamental parameters to understand how molecular gas feeds regions of massive SF in nuclear environments.

Tracers for high-density molecular gas are transitions of molecules with large electric dipole moments (relative to CO), such as HCN, HCO$^+$, CS, or ammonia (NH$_3$). Those molecules are excited at densities $\gtrsim 10^4$ cm$^{-3}$, which we refer to as dense gas.

The specific tetrahedral structure of ammonia that permits the tunneling of the nitrogen atom through the plane defined by the three hydrogen atoms causes inversion doublets. Since the energy difference between the two states of a given inversion doublet does only weakly depend on the rotational quantum numbers $J$ and $K$, a vast range of molecular excitation can be covered with just one set of radio receivers.

For the metastable ($J = K$) inversion lines, at the bottom of each $K$-ladder, radiative decay is extremely slow and the rotation temperature $T_{\text{rot}}$ (the temperature defined by the populations of the different rotational levels) is to first order similar to the kinetic temperature ($T_{\text{kin}}$) of the dense molecular gas (e.g., Ho & Townes 1983; Walmsley & Ungerechts 1983; Stutzki & Winnewisser 1985; Martin & Ho 1986; Ungerechts et al. 1986; Danby et al. 1988; Flower et al. 1995; Hüttemeister et al. 1995). Deviations between $T_{\text{rot}}$ and $T_{\text{kin}}$ at higher temperatures are well described by radiative transfer large velocity gradient (LVG) models. Ammonia is the brightest molecular species with those properties, which makes it an important and easy-to-use thermometer. According to the orientation of the hydrogen spins, two different variants of
ammonia can be distinguished: ortho-NH$_3$ (all three hydrogen spins are parallel) and para-NH$_3$ (one spin is antiparallel). This restricts the rotational $(J, K)$ states to $K = 3n$ ($n$ is an integer, $J$ the quantum number of the total angular momentum, and $K$ its projection onto the symmetry axis of the molecule) for ortho-ammonia and $K \neq 3n$ for para-ammonia (e.g., Townes & Schawlow 1955; Ho & Townes 1983). Since the lowest state of ammonia belongs to ortho-ammonia, an ortho-ammonia–to–para-ammonia ratio exceeding unity is expected if the formation and equilibration of NH$_3$ are performed in an environment with a low-energy content (e.g., Takano et al. 2002, hereafter T02).

Up to now, rotational ammonia temperatures in extragalactic objects were only derived from single-dish observations (e.g., Martin & Ho 1986; Henkel et al. 2000; Takano et al. 2000; Weiss et al. 2001a; T02; Mauersberger et al. 2003, hereafter M03), which restricted the temperature measurements to global averages over a few hundred parsecs. The only interferometric (VLA$^2$) extragalactic ammonia maps were presented by Ho et al. (1990) for IC 342. The signal-to-noise ratio (S/N) of these maps, however, was not good enough for temperature determinations. In this paper we present interferometric maps of ammonia toward the core of the galaxy NGC 253 observed with the Australia Telescope Compact Array (ATCA$^3$). The observations have a linear resolution of $\sim 5''$ (corresponding to 65 pc) along the major axis and are therefore a clear improvement over single-dish observations presented by T02 and M03. NGC 253 is one of the most luminous starburst galaxies (distance adopted here: 2.6 Mpc, Puche & Carignan 1988; but see Karachentsev et al. 2003: 3.9 Mpc). The current SFR of 3 M$_\odot$ y$^{-1}$ (Radovich et al. 2001) is mainly concentrated in the inner $\sim 200$ pc. The starburst, likely fed by gas streaming toward the center along a prominent bar, is visible at virtually all wavelengths (e.g., Ulvestad & Antonucci 1997; Engelbracht et al. 1998; Forbes et al. 2000; Strickland et al. 2002; Jarrett et al. 2003). Furthermore, feedback from massive stars in the form of strong stellar winds and supernova explosions heats the surrounding gas and a galactic wind is observable in NGC 253 up to 8 kpc above the disk (Strickland et al. 2002). Molecular lines have been abundantly found toward the nucleus of NGC 253 (e.g., Turner 1985; Jackson et al. 1995; Houghton et al. 1997; García-Burillo et al. 2000; Bradford et al. 2003; M03; Martin et al. 2003; Paglione et al. 2004; Henkel et al. 2004; Bayet et al. 2004), and, in fact, almost every molecule that was detected in an extragalactic object has also been detected in NGC 253.

In § 2 we describe the observational parameters of our ATCA ammonia data, as well as the data reduction techniques. This is followed by the presentation of the data in § 3. We discuss the ammonia and continuum observations in § 4 and summarize the paper in § 5.

2. OBSERVATIONS AND DATA ANALYSIS

Observations of the para-NH$_3$ (1, 1) and (2, 2) inversion lines were simultaneously performed with the ATCA on 2003 September 5. On 2004 April 26, the ATCA was used to simultaneously observe ortho-NH$_3$ (3, 3) and (6, 6). During both observations, the ATCA was in the compact EW 367 array configuration. The bandwidths were chosen to be 64 MHz for each line, centered on the redshifted frequencies of 23.6755, 23.7035, 23.851, and 25.036 GHz, respectively (primary half-power beamwidths: $\sim 2''$). Each of the frequency bands was split into 64 channels, resulting in a channel width of 1 MHz or $\sim 12.65$ km s$^{-1}$.$\sim 11.96$ km s$^{-1}$ in the case of the NH$_3$ (6, 6) line). For the calibration of the NH$_3$ (1, 1) and (2, 2) observations we used Uranus as a flux calibrator, PKS 1921–293 as a bandpass calibrator (integration time $\sim 10$ minutes), and PKS 0023–263 as a phase calibrator (4 minutes after each 20 minute observing interval on NGC 253). The calibrators for the NH$_3$ (3, 3) and (6, 6) observations were the same except that PKS 1934–638 was used to determine the flux scales. Calibration uncertainties are estimated to be $\sim 10\%$. Due to the lower S/N of the NH$_3$ (6, 6) line, we estimate the error for this line to $\sim 20\%$. Relative uncertainties between the different line fluxes do not depend on absolute calibration errors and are $\sim 5\%$. The total NH$_3$ (1, 1) and (2, 2) integration time on NGC 253 was $\sim 8.5$ hr spread over a 12 hr interval yielding a good UV coverage of the east-west interferometer. The NH$_3$ (3, 3) and (6, 6) integration time was $\sim 6$ hr spread over $\sim 7$ hr. This resulted in a reduced UV coverage. Both the XX and the YY polarizations were observed at all frequencies.

The data were reduced with the MIRIAD (Sault et al. 1995) and visualized with the KARMA (Gooch 1996) software packages. After flagging very few corrupted visibilities and discarding edge channels, calibration was applied to the data. Subsequently, the data were Fourier transformed to image data cubes with a gridding of 1" pixel size. Along with the transform, we used natural weighting, which results in a synthesized beam of 18$'' \times 5''$ in size (position angle: $-0.7'$) for the full UV coverage NH$_3$ (1, 1)/(2, 2) data. Continuum maps were produced by averaging line-free channels. Due to sidelobes of the strong emission, the rms noise of the naturally weighted continuum maps is with $\sim 1$ mJy beam$^{-1}$ at 23.6755 and 23.7035 GHz and $\sim 1.5$ mJy beam$^{-1}$ at 23.851 and 25.036 GHz about twice that of the continuum-subtracted channel maps (see below). The continuum maps were subtracted from all channel maps to obtain continuum-free line cubes. Since the UV coverages of the NH$_3$ (1, 1)/(2, 2) and NH$_3$ (3, 3)/(6, 6) cubes differ, we also produced (1, 1) and (2, 2) data cubes restricted to the hour angles set by the NH$_3$ (3, 3)/(6, 6) observations. This resulted in a synthesized beam of 30$'' \times 5''$ and a position angle of $-12'$, which is almost orthogonal to the distribution of the dense gas as seen, e.g., in Peng et al. (1996). The data were Hanning smoothed (which resulted in a velocity resolution about twice the channel width) and CLEANed down to a 1 mJy level (about 2 $\sigma$ rms noise).

For a proper comparison of the line properties, the NH$_3$ (6, 6) and the local sidereal time restricted (1, 1)/(2, 2) cubes were finally smoothed to the spatial resolution of the NH$_3$ (3, 3) data. The channel maps of all data cubes exhibit an rms noise of $\sim 0.6$ mJy beam$^{-1}$. We also produced a superresolved cube of NH$_3$ (3, 3) by convolving the CLEAN components with a circular beam of 5$'' \times 5''$. The superresolved cube is not used for any quantitative analysis but provides a better morphological separation of individual clumps of dense molecular gas. Moment maps were computed by selecting only emission components with a signal of at least 2.5 times above the rms per channel map. In addition, the signal must be visible in at least three consecutive channels to be incorporated. All other data were flagged before producing the integrated intensity, the intensity-weighted velocity, and the velocity dispersion maps (i.e., moments 0, 1, and 2).

3. RESULTS

3.1. Continuum Emission

Spatially unresolved continuum emission was detected in all bands toward the central starburst of NGC 253 at $\alpha = 00^h47^m33^s$, 200 pc. The starburst, likely fed by gas streaming toward the center along a prominent bar, is visible at virtually all wavelengths (e.g., Ulvestad & Antonucci 1997; Engelbracht et al. 1998; Forbes et al. 2000; Strickland et al. 2002; Jarrett et al. 2003). Furthermore, feedback from massive stars in the form of strong stellar winds and supernova explosions heats the surrounding gas and a galactic wind is observable in NGC 253 up to 8 kpc above the disk (Strickland et al. 2002). Molecular lines have been abundantly found toward the nucleus of NGC 253 (e.g., Turner 1985; Jackson et al. 1995; Houghton et al. 1997; García-Burillo et al. 2000; Bradford et al. 2003; M03; Martin et al. 2003; Paglione et al. 2004; Henkel et al. 2004; Bayet et al. 2004), and, in fact, almost every molecule that was detected in an extragalactic object has also been detected in NGC 253.

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2 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

3 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.
The flux density of the continuum source is derived to 520 mJy with an absolute uncertainty of $\pm 10\%$. The flux is in good agreement with the 31.4 GHz flux of 590 mJy reported by Geldzahler & Witzel (1981). The relative uncertainty of the continuum fluxes in the four different bands (assuming a flat spectrum within the narrow frequency range) is only $\pm 5\%$.

3.2. Global Morphology and Velocity Field of the Ammonia Inversion Lines

The resulting ammonia data cubes are shown as channel maps in Figures 1 and 2. Note that for these figures the full UV coverage NH$_3$ (1, 1) and (2, 2) data are used. All ammonia lines are detected, and two major complexes, separated spatially and in velocity space, can be defined: one toward the northeast and a second one toward the southwest of the starburst center. At the starburst center itself, a faint absorption component in

AMMONIA IN NGC 253

TABLE 1

| Region            | $v_{\text{LSR}}$ (km s$^{-1}$) | $\Delta v_{1/2}$ (km s$^{-1}$) | $\int S \, dv$ (Jy km s$^{-1}$) |
|-------------------|-------------------------------|-------------------------------|---------------------------------|
| NH$_3$ (1, 1)     |                               |                               |                                 |
| Northeast         | 191                           | 94                            | 2.00                            |
| Southwest         | 304                           | 76                            | 2.72                            |
| Total             |                               |                               | 4.72                            |

| NH$_3$ (2, 2)     |                               |                               |                                 |
| Northeast         | 178                           | 86                            | 1.48                            |
| Southwest         | 293                           | 66                            | 2.70                            |
| Total             |                               |                               | 4.18                            |

| NH$_3$ (3, 3)     |                               |                               |                                 |
| Northeast         | 180                           | 63                            | 3.91                            |
| Southwest         | 304                           | 74                            | 4.19                            |
| Total             |                               |                               | 8.10                            |

| NH$_3$ (6, 6)     |                               |                               |                                 |
| Northeast         | 179                           | 60                            | 0.60                            |
| Southwest         | 282                           | 72                            | 1.35                            |
| Total             |                               |                               | 1.95                            |

**Notes.**—Here $v_{\text{LSR}}$ is the LSR peak velocity, $\Delta v_{1/2}$ is the line FWHM, and $\int S \, dv$ is the integrated flux. The errors of the velocities are $\pm 20$ km s$^{-1}$ $\pm 40$ km s$^{-1}$ for the (6, 6) line due to the lower S/N, and the fluxes are accurate to $\pm 10\%$ [NH$_3$ (6, 6): 20\%].
NH₃ (1, 1), (2, 2), and (6, 6) and some broad (3, 3) emission are detected against the 1.2 cm radio continuum (§ 3.1). The northeast component covers a velocity of ~100–240 km s⁻¹ in the LSR system (systemic LSR velocity of NGC 253: 234 ± 2 km s⁻¹; Whiting 1999), whereas the southwest part covers ~240–380 km s⁻¹. The total NH₃ spectra, encompassing both the southwest and the northeast components, are shown in Figure 3 and their properties are listed in Table 1. A comparison with the single-dish observations of M03 and T02 shows that all flux has been recovered by the ATCA observations. In Figure 3 we overlay a CO spectrum for comparison. The CO data were observed with the Owens Valley Radio Interferometer (courtesy of M. Dahlem and F. Walter) and were smoothed to the ATCA beam size and scale in order to achieve the same beam size and position angle. The contours are at the 10% level and are spaced by 2 K km s⁻¹. The data have been reduced using the full 12 hr UV coverage. The gray scale is from 0 to 30 K and the contours of the restricted UV coverage NH₃ (1, 1) emission (thick) in order to achieve the same beam size and position angle. The contours are at the same spacing and scale as in (a), and the gray scale ranges from 0 to 25 K km s⁻¹. Note that, for clarity, we do not show velocity contours in the central 210–270 km s⁻¹ range. (d) Same as (c), but for the NH₃ (3, 3) emission. In all panels, the position of the 1.2 cm continuum source is marked by a star and the corresponding beams are shown in the lower left corners. All panels are on the same scale.

NH₃ (1, 1), (3, 3) peak, however, is shifted slightly closer to the starburst center as compared to the peaks seen in all other inversion lines. The separation of the (3, 3) emission from the other inversion lines in that region is about the extent of the minor-axis beam (~5″) and is therefore significant (Fig. 4b). Such spectral and morphological differences of the NH₃ (3, 3) line are somewhat surprising, as both the (3, 3) and (6, 6) lines are emitted by ortho-NH₃ (see § 4.2).

Toward the southwest region of NGC 253 the intensity-weighted, first-moment velocity field is rather regular and increases with rising galactocentric distance from vLSR ~ 240 to 380 km s⁻¹. The situation is somewhat different in the northeast: the NH₃ velocities decline from v ~ 200 to 150 km s⁻¹ at a distance of about 8″ from the central starburst region and then rise again to values of ~200 km s⁻¹. This trend is already visible in the intensity-weighted velocity maps in Figure 4 but becomes more prominent in the position-velocity (PV) diagram shown in
Figure 5. Line widths are ~40–90 km s\(^{-1}\), irrespective of galactocentric radius (see Fig. 4 and Table 2).

4. DISCUSSION

4.1. The Star Formation Rate in the Nucleus of NGC 253

Ulvestad & Antonucci (1997) showed that most of the radio continuum in the center of NGC 253 is emitted by H\(\alpha\) regions and supernova remnants and that no clear evidence for an active galactic nucleus exists. Therefore, the measured 1.2 cm radio continuum emission can be used to estimate SFRs. To do so, we use the equations given in Haarsma et al. (2000; see also Condon 1992), and using the 1.2 cm continuum flux of 520 ± 52 mJy, we derive the nuclear SFR of NGC 253 to 2.8 ± 0.3 \(M_\odot\) yr\(^{-1}\). This is in excellent agreement with FIR data (SFR\(_{\text{FIR}}\) = 2.6–3.3 \(M_\odot\) yr\(^{-1}\); Radovich et al. 2001).

4.2. Properties of Individual Dense Gas Clumps

In the superresolved data cubes (Fig. 5a) six clumps can be identified: clumps A, B, and C are located toward the southwest and clumps D, E, and F toward the northeast. Only clumps C and D, however, are symmetrical in position and velocity to the starburst center. No symmetry is observed between complexes E/F and A/B. This indicates that an inner ring rotating like a solid body may exist, but no such structure can explain the velocity field at larger radii of ~200 pc. The SiO and H\(^{13}\)CO\(^+\) distributions are similar to that of NH\(_3\), and García-Burillo et al. (2000) interpret the two inner clumps being at the inner Lindblad resonance whereas the outer clumps are the vertices of the trailing spiral arms across the outer Lindblad resonance. This interpretation can potentially explain the kinematic asymmetry of the outer parts of the dense gas. The morphology and kinematics of the NH\(_3\) complexes are also in general agreement with CS data (a different tracer for dense gas) presented in Peng et al. (1996). Clumps with CS emission that may be attributed to the ammonia complexes E and F, however, are shifted ~5" toward the center with respect to NH\(_3\). Peng et al. (1996) show that some CS emission in the southwest, the receding part of NGC 253, is below the systemic velocity. Toward the approaching northeast region some gas is found with velocities above the systemic velocity. They explain those features as signatures (\(x_1\) and \(x_2\) orbits) of dense gas moving in a bar potential (see also Sorai et al. 2000; Das et al. 2001). Our NH\(_3\)
data do not show those specific signatures, which, however, may be due to the weakness of the emission toward those regions.

Measured from the starburst center, the ammonia emission extends \( \sim 200 \) pc toward the northeast and \( \sim 250 \) pc toward the southwest. We define eight positions for a more detailed analysis: positions P1–P3 correspond to the centers of clumps A, B, and C, and P4 is located on the 1.2 cm continuum emission. In order to account for the small displacement of the NH\(_3\) (3, 3) emission with respect to the other inversion lines in the innermost northeast complex, P5 is defined to be toward the NH\(_3\) (3, 3) peak and P6 coincides with the peaks of NH\(_3\) (1, 1), (2, 2), and (6, 6). Finally, P7 and P8 are defined to be on the respective peaks of clumps E and F. The positions of P1–P8 are displayed in Figure 6, and their line properties are listed in Table 2. Ammonia spectra of those positions are shown in Figure 7. In the same figure, we also show CO spectra for comparison. The individual ammonia line widths and brightness peaks toward the southwest do not differ significantly from those toward the northeast region despite the larger total, spatially integrated flux of the southwest region (see \( \S \) 3.2, Fig. 3, and Table 1). This implies that there is more extended emission toward the southwest than the northeast. The CO spectra for P4–P7 are very broad and some subcomponents extend well to the other side of the systemic velocity of NGC 253. This is similar to the velocity structure of CS (Peng et al. 1996) but, as noted above, cannot be extracted from our ammonia data.

NH\(_3\) (1, 1), (2, 2), and (6, 6) absorption is seen toward the 1.2 cm continuum source at P4. If a similar absorption feature for NH\(_3\) (3, 3) exists, it is blended with emission of this line. The reason for the NH\(_3\) (3, 3) emission at P4 may be obvious from the contours of the PV diagram in Figure 5, where a faint, central NH\(_3\) (3, 3) feature extends from the systemic velocity of NGC 253 to \( \sim 400 \) km s\(^{-1}\). A similar feature is seen in OH (Turner 1985) and SiO (García-Burillo et al. 2000). García-Burillo et al. (2000) speculate that this may be evidence for molecular outflows from

Fig. 6.—Total ammonia column density map and contours, computed by the sum of the column densities derived from NH\(_3\) (1, 1), (2, 2), (3, 3), and (6, 6) \([N_{\text{NH}_3}]\). The contour levels start at and are spaced by \( 1 \times 10^{14} \) cm\(^{-2}\). Overlaid are the locations of the positions P1–P8 as white crosses and the 1.2 cm continuum peak, which corresponds to P4, as a black star. The size of the beam is shown in the lower left corner.

Fig. 7.—Ammonia spectra toward positions P1–P8. Overlaid are corresponding CO spectra scaled by a factor of 0.1 (CO data courtesy of M. Dahlem and F. Walter). Dotted vertical lines mark the systemic velocity of NGC 253.
the starburst. Our elongated beam toward the possible outflow direction, however, inhibits the identification of a spatial offset of the faint plume along the minor axis of NGC 253. Therefore, we cannot exclude other line-broadening mechanisms. The reason why we only observe this feature in NH$_3$ (3, 3) but not in (2, 2) and (6, 6) absorption features, accompanied by (1, 1), (2, 2), and (6, 6) absorption features, is also Schilke et al. (1998) and Guilloteau et al. (1998) show that at H$_2$ volume densities of $10^4$–$10^5$ cm$^{-3}$ the statistical weights given as $E_0(1, 1)$ and $E_0(2, 2)$, and (6, 6) absorption features, are observed toward the nuclear continuum of NGC 253. Toward the same central region of NGC 253 OH and H$_2$O masers are already known to exist (Fray et al. 1998; Henkel et al. 2000). Thus, NH$_3$ may represent the third molecular species known to exhibit maser emission in the central environment of NGC 253. If confirmed, it would be the first extragalactic NH$_3$ maser ever detected (NH$_3$ would then be the sixth molecule showing maser emission in extragalactic objects; for OH, H$_2$O, CH$_3$OH, SiO, see Waelchew 1971; Churchwell et al. 1977; Whiteoak et al. 1980; Baan et al. 1986; van Loon et al. 1996).

### 4.3. Rotational Temperatures

As indicated in § 1, ammonia can be used to determine rotational temperatures of the dense molecular gas. To derive rotational temperatures from ammonia in emission, populations of more than one metastable ($J = K$) inversion doublet have to be determined. Assuming optically thin line emission, the column densities of their upper states $N_u$ can be derived via

$$N_u(J, K) = \frac{7.77 \times 10^{13}}{\nu} \frac{J(J + 1)}{K^2} \int T_{\text{mb}} d\nu$$  \hspace{1cm} (1)

(Henkel et al. 2000), where $N_u$ is given in units of cm$^{-2}$, the frequency $\nu$ in GHz, the main-beam brightness temperature $T_{\text{mb}}$ in K, and the velocity $v$ in km s$^{-1}$.

For ammonia in absorption, the column densities of the different populations cannot be determined without the knowledge of the excitation temperature $T_{\text{ex}}$ across an individual inversion doublet. The following equation applies:

$$\frac{N(J, K)}{T_{\text{ex}}} = 1.61 \times 10^{14} \frac{J(J + 1)}{K^2\nu} \tau \Delta v_{1/2}$$ \hspace{1cm} (2)

(Hüttemeister et al. 1995), with $\Delta v_{1/2}$ denoting the FWHM of the line in km s$^{-1}$. The optical depth $\tau$ is derived from the brightness temperatures of the line $T_L$ and the continuum $T_C$ by

$$\tau = -\ln \left(1 - \frac{T_L}{T_C}\right).$$ \hspace{1cm} (3)

From the different $N_u$ of the metastable ($J = K$) inversion lines, the rotational temperatures $T_{12}'$ can be derived using

$$\frac{N_u(J', J)}{N_{u}(J, J)} = \frac{g_{op}(J')}{g_{op}(J)} \exp \left(\frac{-\Delta E}{T_{12}'}\right)$$ \hspace{1cm} (4)

(corrected version of the equation given in Henkel et al. 2000). Parameter $\Delta E$ is the energy difference between the NH$_3$($J'$, $J'$) and the NH$_3$(J, J) levels in K [41.2 K between NH$_3$(1, 1) and (2, 2), and 284.4 K between NH$_3$(3, 3) and (6, 6)], and $g_{op}$ are the statistical weights given as $g_{op} = 1$ for para-ammonia [NH$_3$ (1, 1) and (2, 2)] and $g_{op} = 2$ for ortho-ammonia [NH$_3$ (3, 3) and (6, 6)]. This equation is applicable for emission and is also valid for absorption lines when it is assumed that both transitions have the same $T_{\text{ex}}$. Our LVG analysis (see below) shows that excitation temperatures of NH$_3$ (1, 1) and (2, 2) are indeed very similar, which is not necessarily the case for NH$_3$ (3, 3) and (6, 6).

In Table 3 the column densities of the upper levels $[N(J, K)/T_{\text{ex}}$ for P4] and the rotational temperatures of the ammonia spectra at positions P1–P8 are listed. The column densities of the para-NH$_3$(1, 1) and ortho-NH$_3$(3, 3) transitions may differ by up to a factor of 2 with a slight trend for $N_u(1, 1)$ to be larger. In spite of their higher statistical weights, the (2, 2) and (6, 6) levels are less populated than the lower counterparts of the respective ammonia variant. The rotational temperatures $T_{12}$ [using

| Parameter | P1 | P2 | P3 | P4$^*$ | P5 | P6 | P7 | P8 | Northeast | Southwest |
|-----------|----|----|----|--------|----|----|----|----|-----------|-----------|
| $N_u(1, 1)$ (x10$^{13}$ cm$^{-2}$) | 7.87 | 9.42 | 5.53 | 6.99 | 6.39 | 8.91 | 7.98 | 7.59 | 1.74 | 2.10 |
| $N_u(2, 2)$ (x10$^{13}$ cm$^{-2}$) | 6.01 | 5.39 | 4.93 | 15.4$^*$ | 3.24 | 5.56 | 4.1 | 3.91 | 0.95 | 1.57 |
| $N_u(3, 3)$ (x10$^{13}$ cm$^{-2}$) | 6.97 | 5.80 | 7.76 | 8.73 | 9.63 | 8.83 | 6.94 | 4.76 | 2.19 | 2.30 |
| $N_u(6, 6)$ (x10$^{13}$ cm$^{-2}$) | 1.66 | 1.15 | 1.22 | 14.2$^*$ | 1.28 | 1.63 | 1.13 | 0.59 | 0.29 | 0.45 |
| $N_{1236}(\text{NH}_3)$ (x10$^{13}$ cm$^{-2}$) | 46.8 | 43.5 | 38.9 | ... | 41.1 | 49.8 | 40.3 | 33.7 | 10.4 | 12.8 |
| $N(\text{H}_2)$ (x10$^{24}$ cm$^{-2}$) | 22.7 | 24.9 | 27.5 | 3.24 | 5.56 | 4.1 | 3.91 | 0.95 | 1.57 | 7.2 |
| $N_{1236}(\text{NH}_3)/N(\text{H}_2)$ (x10$^{-9}$) | 20.6 | 17.5 | 14.2 | ... | 19.5 | 24.8 | 24.3 | 20.2 | 16.5 | 17.8 |
| $T_{12}(K)$ | 46 | 39 | 66 | 88$^*$ | 35 | 42 | 35 | 35 | 37 | 51 |
| $T_{16}(K)$ | 138 | 127 | 115 | ... | 108 | 123 | 117 | 105 | 108 | 127 |

Notes.—$N_u$ are the column densities of the upper levels, $N_{1236}(\text{NH}_3)$ are the combined measured column densities (assuming that the lower levels are populated as the upper levels, but ignoring all contributions from other lines), and $N_{1236}(\text{NH}_3)/N(\text{H}_2)$ are the abundances based on the $N_{1236}(\text{NH}_3)$ column densities. $T_{12}$ and $T_{16}$ are the rotational temperatures using the para-ammonia (1, 1) and (2, 2) and the ortho-ammonia (3, 3) and (6, 6) inversion lines, respectively. Whereas the absolute uncertainties of the column densities are $\sim 10\%$, [NH$_3$ (6, 6): 20\%], the relative uncertainties are $\sim 5\%$. $T_{12}$ and $T_{16}$ exhibit a statistical 1 $\sigma$ error of 2 and 5 K, respectively. $^*$ The column densities listed for the NH$_3$ (1, 1), (2, 2) and (6, 6) absorption components are actually the ratio of the column density to the excitation temperature $N/T_{\text{ex}}$ in units of 10$^{13}$ cm$^{-2}$ K$^{-1}$ (see § 4.3).
the para-ammonia (1, 1) and (2, 2) inversion lines] are in the range of 35–65 K for the emission components and 88 K (statistical 1σ error including calibration uncertainties: 2 K) for the absorption component. The rotational temperatures of ortho-NH₃ [T₃₆; using NH₃ (3, 3) and (6, 6)] are in the range of 105–140 K (see Table 3). In Figure 8 we compare Boltzmann plots (also referred to as rotational diagrams) of our analysis with those from the single-dish observations presented by M03 and T02. Since the northeast and southwest components are clearly discernible in velocity space, the different regions can be separated in the single-dish data. Because parts of the analyses in T02 and M03 are different from ours (e.g., M03 fitted a single rotation temperature using data of all transitions), we extracted the brightness temperatures from their papers and followed our methods described above. In the Boltzmann plot, the slopes between different inversion transitions represent rotational temperatures with steep slopes corresponding to low rotational temperatures. We find that our column densities are very similar to those of M03 and exceed those of T02. T02 did not observe the NH₃ (6, 6) line and could therefore not derive T₃₆. Their T₁₂ is lower than ours for both the southwest and northeast components but confirms the trend of higher temperatures toward the southwest. The temperature distribution is reversed in the analysis of M03. Using HCN and CO data, Paglione et al. (2004) independently find higher temperatures toward the southwest than toward the northeast, which agrees with our analysis and that of T02.

4.4. LVG Analysis

4.4.1. LVG Models

As shown by Walmsley & Ungerechts (1983) and Danby et al. (1988), kinetic temperatures and T₁₂ and T₃₆ rotational temperatures of NH₃ are similar up to 20 and 60 K, respectively. Our rotational temperatures, however, are above those values and therefore the kinetic temperatures exceed the rotational temperatures considerably. To derive kinetic temperatures, we applied our LVG models using collisional rate coefficients and cross sections of Danby et al. (1988; see also Schöier et al. 2005). The LVG models predict column densities for all levels that depend on the kinetic temperature, the H₂ volume density, a velocity gradient, and the temperature of the cosmic microwave background (CMB). For our calculations we set the CMB temperature to 2.73 K and the velocity gradient to dv/dr = 1 km s⁻¹ pc⁻¹. In the case of optically thin lines, which is considered here, NH₃ column densities scale linearly with NH₃ abundances. In Figure 9 the column densities in the upper (1, 1) to (6, 6) levels are shown for different models using an ortho-ammonia–to–para-ammonia (o/p) ratio of unity. The densities (n_u^{LVG}) are displayed in the

![Fig. 8.—Boltzmann plot of the different ammonia transitions for the northeast (solid lines, filled symbols) and southwest (dotted lines, open symbols) molecular complexes. The horizontal axis denotes the energies of the levels above the ground state. The circles are our data, while the triangles are taken from M03 and are shifted down by 1 dex on the vertical axis. The squares display the results from T02 shifted down by 2 dex. The numbers mark the rotational temperatures in K for the different slopes.](image)

![Fig. 9.—LVG models. Shown are upper level column densities (corrected for their individual statistical weights as used in Boltzmann plots) of NH₃ (1, 1), (2, 2), (3, 3), (4, 4), (5, 5), and (6, 6) as a function of (a) logarithmic H₂ volume density (kinetic temperature fixed at T_kin = 100 K), (b) kinetic temperature (at an H₂ density of 10⁵ cm⁻³), and (c) the models of (b) as they appear in a Boltzmann plot (kinetic temperatures: 10–100 K, spaced by 10 K). The dotted lines mark the expected slopes if T_rot would be equal to T_kin. The LVG column densities can be converted into real column densities via eq. (5). The models shown are derived for a fractional NH₃ abundance relative to H₂ of 10⁻⁶, a velocity gradient of dv/dr = 1 km s⁻¹ pc⁻¹, and o/p = 1. In (a) and (b) the models are displayed for the (1, 1) to (6, 6) inversion states from top to bottom, respectively.](image)
The models with varying $o/p$ ratio for the northeast and southwest regions. In the Boltzmann plots, the solid lines connect the data points, whereas the dotted lines connect the modeled densities with $o/p = 1$ (triangles). The dashed lines connect the results of the LVG fits with a variable $o/p$ (circles). All points for the southwest region are shifted down by 1 dex. Note that the models with varying $o/p$ and the data points are very similar, in particular for the NH$_3$(3, 3) measurements. The results of the different fits are labeled in the plot (see also Table 4).

![Comparison of one-temperature LVG models with $o/p = 1$ and with fitted $o/p$ ratios for the northeast and southwest regions.](image)

Fig. 10.—Comparison of one-temperature LVG models with $o/p = 1$ and with fitted $o/p$ ratios for the northeast and southwest regions. The computed ammonia column densities of the metastable lines in interstellar space were found at densities $10^4$ cm$^{-3}$, and we expect that the densities of the environmental region from which the ammonia is emitted in NGC 253 are more and more constant and the curves in the Boltzmann plots (Fig. 9c) are spaced by smaller intervals. As expected, the slopes between the data points at a given kinetic temperature are steeper than those for $T_{\text{rot}} = T_{\text{kin}}$. In other words, rotational temperatures underestimate kinetic temperatures (see above). The most distinctive changes in slope of $T_{\text{rot}}$ are predicted to be at the NH$_3$ (3, 3) transition and are most prominent at kinetic temperatures $\gtrsim 50$ K. Without using radiative transfer codes, the closest match between $T_{\text{rot}}$ and $T_{\text{kin}}$ is therefore provided by all transitions at $T_{\text{kin}} \lesssim 50$ K and by the highest states including (3, 3) at $T_{\text{kin}} \gtrsim 50$ K.

### 4.4.2. Kinetic Temperatures

We attempted to fit the LVG models to the measured ammonia transitions at the different positions toward NGC 253. To do so, we applied one- and two-temperature models to the data. The second temperatures in the latter models, however, are usually very similar to the first temperatures and are therefore not required. One-temperature fits are shown in Figure 10 for the northeast and southwest regions. In general, the one-temperature fits with $o/p = 1$ were underestimating the NH$_3$(3, 3) column densities but provide reasonable fits to the southwest spectra. Still, the fits are substantially improved when the $o/p$ ratio is treated as a free parameter. In that case, the data and the models are virtually indistinguishable. The results of the fits are listed in Table 4. We estimate the errors of the fits including the free $o/p$ parameter to $\sim 20\%$.

The resulting kinetic temperatures are $\sim 200$ K in the southwest and $\sim 140$ K in the northeast. Those values are in agreement with the analysis of Rigopoulou et al. (2002). They use infrared Infrared Space Observatory (ISO) SWS data to determine H$_2$ excitation temperatures of the molecular gas. In addition to two phases with much higher temperatures, they detect H$_2$ at a temperature of $\sim 200$ K. Based on Spitzer and near-infrared data, Devost et al. (2004) and Pak et al. (2004) show that toward the southwest the strengths of the H$_2$ (0–0) $S(1)$ and (1–0) $S(1)$ lines are rather high than those toward the northeast, indicating a larger amount of warm gas toward the southwest. This result corroborates our derived temperature difference between the northeast and southwest regions. Temperatures in the observed range may be explained by shock heating as proposed for the central Galactic region (e.g., Flower et al. 1995; Hüttemeister et al. 1995; Martín-Pintado et al. 2001) and also for NGC 253 itself and other starburst galaxies (e.g., García-Burillo et al. 2000; Devost et al. 2004; Pak et al. 2004). Other processes, such as ion slip or cosmic-ray heating, and dynamic heating by the bar may also have an influence on the temperature of the dense gas. The kinetic temperatures as a function of galactocentric distance are displayed for the individual positions P1–P8 and the entire northeast and southwest regions.

### TABLE 4

| Parameter                                      | P1   | P2   | P3   | P5   | P6   | P7   | P8   | Northeast | Southwest |
|------------------------------------------------|------|------|------|------|------|------|------|-----------|-----------|
| $T_{\text{kin}}$ (K)                           | 214  | 174  | 192  | 149  | 155  | 128  | 151  | 136       | 172       |
| $o/p$                                          | 1.0  | 0.89 | 1.2  | 2.4  | 1.7  | 1.5  | 1.3  | 2.8       | 1.2       |
| $N$(NH$_3$) ($\times 10^{13}$ cm$^{-2}$)       | 79.5 | 64.1 | 71.1 | 106  | 113  | 81.7 | 62.5 | 32.4      | 23.5      |
| $N$(NH$_3$)/$N$(H$_2$) ($\times 10^{-9}$)      | 34.6 | 27.3 | 24.0 | 35.9 | 45.2 | 41.6 | 33.6 | 34.8      | 29.9      |
| $M$(NH$_3$) ($M_{\odot}$)                      | ...  | ...  | ...  | ...  | ...  | ...  | ...  | ...       | ...       |
| $T_{\text{kin}}$($o/p = 1$) (K)                | 218  | 168  | 209  | 236  | 196  | 149  | 166  | 230       | 189       |

Notes.—Listed are the best parameters with a variable $o/p$ ratio: the kinetic temperature $T_{\text{kin}}$, the ortho-ammonia–to–para-ammonia abundance ratio ($o/p$), the total ammonia column densities $N$(NH$_3$), the ammonia abundances $N$(NH$_3$)/$N$(H$_2$), and ammonia masses $M$(NH$_3$). In addition, we show the kinetic temperatures that are the results of fits with an $o/p$ ratio of unity [$T_{\text{kin}}(o/p = 1)$]. The errors are estimated to be $\sim 20\%$. 

The ammonia abundances are most sensitive to changes in $T_{\text{kin}}$. At higher temperatures, the ratios between the weighted column densities become more and more constant and the curves in the Boltzmann plot (Fig. 9c) are spaced by smaller intervals. As expected, the slopes between the data points at a given kinetic temperature are steeper than those for $T_{\text{rot}} = T_{\text{kin}}$. In other words, rotational temperatures underestimate kinetic temperatures (see above). The most distinctive changes in slope of $T_{\text{rot}}$ are predicted to be at the NH$_3$ (3, 3) transition and are most prominent at kinetic temperatures $\gtrsim 50$ K. Without using radiative transfer codes, the closest match between $T_{\text{rot}}$ and $T_{\text{kin}}$ is therefore provided by all transitions at $T_{\text{kin}} \lesssim 50$ K and by the highest states including (3, 3) at $T_{\text{kin}} \gtrsim 50$ K.
southwest regions in Figure 11a. Whereas the temperature variations within the southwest and northeast regions are not significant, the temperature difference between the two sides of the nucleus is notable. Some additional heating may therefore have occurred in the southwest of NGC 253. For possible mechanisms, see the end of §4.4.4 and §4.5.

4.4.3. The Ortho-Ammonia–to–Para-Ammonia Ratio

The o/p ratio depends on the energy that is transferred to the NH$_3$ molecule during its formation and equilibration (see §1). At low energies, only the lowest (0, 0) state can be populated, which belongs to ortho-ammonia. This results in an increase of the o/p ratio. Due to the very slow decay of the metastable inversion states, the o/p ratio is not significantly altered once the formation and equilibration processes are completed (see, e.g., Cheung et al. 1969; Ho & Townes 1983). As shown in T02, the theoretical o/p ratio is about unity at formation temperatures above \( \sim 30 \text{ K} \) and o/p rises steeply at lower temperatures. The o/p ratio therefore offers an archaeological view on the initial conditions of the molecular gas during its formation.

We derive o/p ratios of \( \sim 1 \) in the southwest region, which would correspond to an NH$_3$ formation temperature above \( \sim 30 \text{ K} \) (see Fig. 3 in T02). In the northeast region o/p is with \( \sim 1.5–2.5 \) significantly larger (Table 4 and Fig. 11b). Such o/p ratios suggest lower ammonia formation temperatures of \( \sim 15–20 \text{ K} \) toward the northeast. This result is in agreement with the derived kinetic temperatures, which are also higher in the southwest region.

Since LVG models are rarely applied when analyzing extragalactic NH$_3$ emission, o/p ratios are usually calculated in a different way, making use of deviations from a constant $T_{12}$ rotational temperature model (a single line in the Boltzmann plot; see, e.g., T02; Takano et al. 2000). As shown in Figure 10, this approach may provide reasonable o/p values when adjusting the
ortho-NH$_3$ (3, 3) column densities to the extrapolated para-NH$_3$ $T_{12}$ temperature (note that the kinetic temperatures of the LVG models with a fixed $o/p = 1$ and a free $o/p$ are similar; Table 4). This approach fails, however, when the ortho-NH$_3$ (6, 6) column densities are scaled to match the extrapolated $T_{12}$. The best method without the application of radiative transfer models is to adjust para-NH$_3$ (4, 4) or (5, 5) weighted column densities to $T_{36}$ (see Fig. 9c).

4.4.4. Ammonia Column Densities, Abundances, and Masses

Total ammonia column densities are calculated by adding up the column densities derived for the populations of the individual rotational levels. A rough estimate is given by the sum of the observed levels $N_{1236}$(NH$_3$) = 2 $\sum_{J=1,2,3,6} N_a(J, J)$ (Table 3). The factor of 2 has been introduced to accommodate the populations of the lower inversion levels (which contribute equally to the column densities due to the low-energy difference between upper and lower states of $\sim$1 K). A map of the spatial $N_{1236}$(NH$_3$) distribution is shown in Figure 6. The column densities for the individual clumps are in the range of $\sim$(30–50) $\times$ 10$^{13}$ cm$^{-2}$ (Table 3). Averaged over the entire northeast and southwest regions, however, the NH$_3$ column densities drop to $\sim$10 $\times$ 10$^{13}$ cm$^{-2}$ toward the northeast and to $\sim$13 $\times$ 10$^{13}$ cm$^{-2}$ toward the southwest, due to the inclusion of large-scale diffuse emission between the individual complexes A–F. Therefore, both regions within NGC 253 exhibit similar averaged NH$_3$ columns.

Using only the observed values, however, underestimates the true column densities due to the contributions of the other ammonia levels. The LVG models predict that collisional excitation of the non-metastable levels leads to populations about 3 orders of magnitude below those of metastable levels. The column densities of the non-metastable levels may, however, increase substantially by infrared pumping (e.g., Mauersberger et al. 1985), which is not incorporated in our code. Among the metastable levels, the most prominent are the NH$_3$ (0, 0), (4, 4) and (5, 5) levels. Adding up all the levels involved in our LVG code [up to the metastable (6, 6) levels], the total NH$_3$ column densities are $\sim$1.5–2.5 times larger than $N_{1236}$, corresponding to column densities of (6–11) $\times$ 10$^{14}$ cm$^{-2}$ for the individual clumps (Table 4). The column densities averaged over the northeast and southwest regions are about 2–3 times lower than the column densities in the peaks.

Ammonia masses within the northeast and southwest regions are derived to $\sim$9 and $\sim$10 $M_\odot$ within the central 2$'$ of NGC 253 (see Table 4).

NH$_3$ abundances are computed relative to the column densities of H$_2$. The latter are derived using the CO data (see § 3.2) with a CO-to-H$_2$ conversion factor of $X_{CO} = 5 \times 10^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. This value was determined for ultraluminous FIR galaxies by Downes & Solomon (1998) and is widely used for starburst galaxies in the literature. For NGC 253 itself, Mauersberger et al. (1996) suggest a similar value of $X_{CO} = 3 \times 10^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ based on single-dish CO data. Note, however, that $X_{CO}$ is not necessarily constant over the entire starburst. Using multi-transition, interferometric CO observations toward the starburst galaxy M82, Weiss et al. (2001b) showed that $X_{CO}$ varies in the range of (3–10) $\times$ 10$^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ along the major axis.

The ammonia abundances derived toward the different positions in NGC 253 are listed in Table 4 and are shown as a function of galactocentric distance in Figure 11d. We also produced a map of the ammonia abundances relative to H$_2$ [based on $N_{1236}$(NH$_3$); see the caveats above], which is shown in Figure 12. The fractional ammonia abundances vary in the range of $(25–45) \times 10^{-9}$. The overall abundances are only slightly larger than those derived for NGC 253 by M03 ($\sim$20 $\times$ 10$^{-9}$). Typical ammonia abundances of Galactic molecular clouds are with $\sim$30 $\times$ 10$^{-9}$ in the same range (e.g., Irvine et al. 1987; Walmsley & Schilke 1993). Note that toward the Galactic center, the ammonia abundances are at least as large as toward Galactic interstellar clouds (e.g., Flower et al. 1995; Goicoechea et al. 2004).

An NH$_3$ abundance gradient is visible along the southwest complex with minimal values near the starburst center (Figs. 11d and 12; note that the abundance between P6 and P5, approaching the center from the northeast, is also decreasing). The abundance toward the southwest varies from $\sim$2.5 $\times$ 10$^{-8}$ to $\sim$3.5 $\times$ 10$^{-8}$ at distances of $\sim$40 and $\sim$250 pc from the nucleus, respectively. A
similar gradient has been found for M82 by Weiss et al. (2001a), varying from \( \sim 2 \times 10^{-10} \) close to the starburst center to \( \sim 6 \times 10^{-10} \) at larger radii. Those values, however, are about 2 orders of magnitude lower than the ammonia abundance in NGC 253. The abundance gradient may be explained by the destruction of NH\(_3\) by photodissociation near the starburst similar to what has been proposed for M82 by Weiss et al. (2001a). Whereas the entire ammonia abundance is raised by liberating NH\(_3\) from grains by shocks (see also § 4.4.2), close to the nucleus of NGC 253 the molecules may be destroyed by photons with energies above \( \sim 4.1 \) eV, the dissociation energy of NH\(_3\). This can potentially explain the NH\(_3\) abundance gradient. The molecular gas, however, may be shielded by photodissociation near the starburst similar to what has been found for M82 by Weiss et al. (2001a), and may dissociate a large fraction of the ammonia molecules (see also § 4.5).

4.5. An Expanding Shell in the Dense Gas

Toward the northern end of the ammonia emission in the southwest region, PV cuts of the data cubes reveal a feature resembling an expanding shell that is visible in all inversion lines (see Fig. 13). Given the elliptic beam of the radio data, the position of this feature is somewhat uncertain. However, the largest contrast between the rim and the center of this shell is found at a location coincident with an X-ray point source detected in ACIS-S3 images taken with the Chandra X-Ray Observatory (ObsID 969) at \( \alpha = 00^h47^m32^s, \delta = -25^\circ17'21''(4) \) (J2000.0). The X-ray spectrum of this source is shown in Figure 13c. We fitted an APEC collisional equilibrium plasma (Smith et al. 2001) with solar metallicity and a power-law model to this source (for the data reduction technique see Ott et al. 2005). Both models provide good fits to the data. The APEC fit results in an absorbing column density of \( N_{\text{H}} = (2.8 \pm 0.3) \times 10^{22} \text{ cm}^{-2} \) (excluding Galactic H\(_i\) emission), a temperature of \( T_{\text{plasma}} = (3.6 \pm 0.7) \times 10^7 \text{ K} \), a flux of \( F = (1.9 \pm 0.7) \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \), and an unabsorbed X-ray luminosity \( (0.3 \sim 6.0 \text{ keV}) \) of \( L_X = (4.7 \pm 0.7) \times 10^{38} \text{ ergs s}^{-1} \). The power-law fit yields \( N_{\text{H}} = (2.9 \pm 0.3) \times 10^{22} \text{ cm}^{-2} \), a photon index of \( \Gamma = 2.3 \pm 0.1 \), and \( L_X = (10.3 \pm 2.1) \times 10^{38} \text{ ergs s}^{-1} \). In Figure 13 we show the APEC fit overlaid on the X-ray spectrum; the power-law fit looks very similar. The X-ray absorbing column density can be compared to that of molecular hydrogen. From the CO data (resolution used here: 5\( ' \)), we derive a luminosity of \( \sim 1.1 \times 10^{41} \text{ K km s}^{-1} \), which translates into a proton column density of \( 3.4 \times 10^{22} \text{ cm}^{-2} \), using a CO-to-H\(_2\) conversion factor of \( 5 \times 10^{18} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1} \) (see § 4.4.4). This value is about twice as large as that derived by X-ray absorption, which suggests that the X-ray point source is embedded in the molecular material.

As shown in Figure 13b, the shell is centered at an LSR velocity of \( \sim 310 \text{ km s}^{-1} \) and expands at \( v_{\exp} \sim 30 \text{ km s}^{-1} \). Its radius is \( \sim 3'' \), which corresponds to \( \sim 40 \) pc at the distance to NGC 253. The dynamical age of the shell is therefore \( \sim 1.3 \) Myr. Using the shell radius and the proton column density derived above, we estimate the mass of the shell to \( \sim 8 \times 10^5 M_\odot \) and its kinetic energy to \( \sim 7 \times 10^{52} \text{ ergs} \). This figure is about 2 \( (\text{power-law model}) \) to 4 \( (\text{APEC}) \) times larger than the energy input of the X-ray source over the lifetime of the shell. Using the Starburst99 models (Leitherer et al. 1999) to derive the starburst properties (for details see Ott et al. 2003) and assuming that the X-ray luminosity is due to thermalized mechanical luminosity, the total energy input matches that of a stellar cluster with a mass of

![Figure 13](image-url)
Very close to the starburst the northeastern, innermost NH$_3$ (3, 3) nucleus. The ammonia components are found at velocities of up to 150 km s$^{-1}$ relative to the systemic velocity of NGC 253. Three individual molecular clouds are identified within those regions on either side of the nucleus. The ammonia components are found at velocities of up to 150 km s$^{-1}$ relative to the systemic velocity of NGC 253. Very close to the starburst the northeastern, innermost NH$_3$ (3, 3) emission peak is closer to the nucleus than the peaks of the other ammonia lines.

The line shapes and the morphology of ammonia are similar to those of other molecular species such as CO, CS, SiO, and H$^{13}$CO$^+$. However, some components traced by those molecules were not detected in NH$_3$, which can partly be attributed to the S/N of our observations.

4. Toward the nuclear continuum source we observe NH$_3$ (1, 1), (2, 2), and (6, 6) in absorption but NH$_3$ (3, 3) in emission. This might indicate the presence of an ammonia maser.

5. From our LVG models we find that for each position toward NGC 253 a one-temperature gas with a nonuniform ortho-para-ammonia abundance delivers excellent agreement with the data, despite different rotational temperatures $T_{12}$ and $T_{36}$. The kinetic temperatures in the northeast region hover around 140 K. In the southwest region they are with about 200 K significantly higher.

6. Whereas the o/p abundance ratio is $\sim 1$ toward the southwest, we derive o/p $\sim 1.5$--2.5 toward the northeast, with the larger values close to the starburst center. Such o/p ratios correspond to NH$_3$ formation temperatures of 30 K and $\sim 15$--20 K toward the southwest and northeast, respectively. Thus, the ammonia formation and kinetic temperatures show the same trend, being warmer in the southwest than in the northeast.

7. Total ammonia column densities are $\sim 3 \times 10^{14}$ cm$^{-2}$ toward the northeast and $\sim 2 \times 10^{14}$ cm$^{-2}$ toward the southwest. For the individual clumps we derive column densities in the range of $(6--11) \times 10^{14}$ cm$^{-2}$. The total ammonia mass adds up to $\sim 20 M_\odot$ with about half of the mass toward either side of the star-forming nucleus. In NGC 253, ammonia abundances toward the most prominent molecular complexes are $(2.5--4.5) \times 10^{-8}$ with respect to H$_2$. Decreasing abundances are measured in the southwest complex toward the starburst center. At the position of the lowest NH$_3$ abundance, prominent dust features are visible in near-infrared 2MASS color images. As the starburst in NGC 253 is slightly shifted toward the southwest, the resulting UV radiation may photodissociate the fragile ammonia molecules predominantly in this region.

8. An expanding shell feature is detected within the southwest molecular complex. The shell coincides with a bright X-ray point source. The absorbing column density of the X-ray source as compared to the total molecular column reveals that this source is likely located inside the shell. The shell has a dynamical age of $\sim 1.3$ Myr and a kinetic energy of $\sim 7 \times 10^{52}$ ergs. This corresponds to the energy input of a stellar cluster with a mass of $\sim 10^5 M_\odot$. An optical identification of this cluster is very difficult due to high visual obscuration. At the position of the shell, the rotational temperature of ammonia is enhanced by a factor of $\sim 2$ over the mean of the southwest region, coincident with a local maximum of H$_2$ excitation temperatures. This supports the scenario that large amounts of energy are injected into the dense gas.

Our study demonstrates the power of interferometric multi-transition ammonia observations to constrain in detail the physical conditions of the various phases of molecular gas in starburst environments. The application of radiative transfer models to the data allows us to determine the conditions with better accuracy than previously possible. Studies of other nearby actively star-forming galaxies will be needed to find out whether NGC 253 provides a typical environment and may therefore be used as a prototype for comparisons with more distant, even more vigorously star-forming objects.

We thank Michael Dahlem for the provision of the CO data. We are also grateful to Rainer Mauersberger and the referee for their comments on the manuscript. C. H. thanks ATNF for support provided during his time spent at ATNF and ATCA. This research...
