New ammonia masers towards NGC 6334I

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ABSTRACT

We report the detection of new ammonia masers in the non-metastable (8,6) and (11,9) transitions towards the massive star-forming region NGC 6334I. Observations were made with the Australia Telescope Compact Array interferometer and the emitting region appears unresolved in the 2.7 × 0.8 arcsec2 beam, with deconvolved sizes less than an arcsecond. We estimate peak brightness temperatures of 7.8 × 103 and 1.2 × 105 K for the (8,6) and (11,9) transitions, respectively. The masers appear coincident both spatially and in velocity with a previously detected ammonia (6,6) maser. We also suggest that emission in the (10,9), (9,9) and (7,6) transitions may also be masers, based on the small linewidths and overlapping velocity ranges with the above masers, as observed with the single-dish Mopra radio telescope.

Keywords: masers – techniques: high angular resolution – stars: formation – ISM: molecules.

1 INTRODUCTION

Ammonia (NH3) is an extremely useful molecular tool for studying the interstellar medium. Many inversion transitions occur in the easily observable 12-mm band. They include transitions from both metastable (J = K) and non-metastable (J > K) levels of ammonia. Hyperfine structure in the metastable transitions is commonly seen, and can be used to derive optical depths, whereas comparison of different (J, K) transitions can yield information on the rotational temperature (e.g. Walmsley & Ungerechts 1983; Danby et al. 1988).

The first suggestion that ammonia may display maser action in interstellar space was made by Wilson, Batrla & Pauls (1982) who noted that (3,3) emission toward W33 was not matched by (1,1), (2,2) and (4,4) transitions, which were all in absorption. They suggested that this may be due to a weak population inversion. Maser emission in ammonia transitions was first unambiguously identified by Madden et al. (1986) in the (9,6) and (6,3) transitions, shortly followed by Mauersberger, Wilson & Henkel (1986) in the (3,3) transition of 15NH3. In addition to these transitions, ammonia masers have been detected in the following transitions: (5,4) (7,5), (9,8), (10,8) (Mauersberger, Henkel & Wilson 1987), (6,5) (Mauersberger, Wilson & Henkel 1988), (5,5) (Cesaroni, Walmsley & Churchwell 1992), (6,6) (Beuther et al. 2007) and (1,1) (Gaume, Wilson & Johnston 1996). 14NH3 (3,3) masers were first detected by Zhang & Ho (1995). Pumping mechanisms for most ammonia masers remain unclear. Metastable transitions of ortho-ammonia, like (3,3), are thought to be collisionally excited (Walmsley & Ungerechts 1983), but such a mechanism will only work for non-metastable transitions where exceedingly high H2 densities between 1010 and 1012 cm−3 are found (e.g. Madden et al. 1986). Madden et al. (1986) suggest two alternative pumping mechanisms for non-metastable transitions: either by a strong infrared radiation field, such as found around a deeply embedded high-mass star, or by a fortuitous overlap of a far-infrared line, which allows a population transfer from a (J, K) inversion level to (J + 1, K).

Ammonia masers are found in regions of high-mass star formation, with the best known example being W51 (Madden et al. 1986; Mauersberger et al. 1987), with other prominent examples being G9.62 + 0.19 (Cesaroni et al. 1992; Hofner et al. 1994) and NGC 6334I (Kraemer & Jackson 1995; Beuther et al. 2007). NGC 6334I forms the focus of this work. It is a nearby (1.7 kpc, Neckel 1978) region of high-mass star formation, traced by bright infrared emission, an ultracompact (UC) HII region, millimetre continuum sources and methanol maser sites. See Beuther et al. (2007) for a more comprehensive summary of characteristics of the region.

2 OBSERVATIONS AND DATA REDUCTION

The initial observations were undertaken with the 22-m Mopra telescope near Siding Spring, Australia. We obtained a spectrum of NGC 6334I at 17h20m53.43s, −35°47′2.2″ (J2000) using position switching on 2006 November 28. We used the new Mopra spectrometer (MOPS) in broad-band mode, which affords us four overlapping intermediate frequencies (IFs) of 2.2 GHz each. Thus we were able instantaneously to cover 8 GHz of frequency space between 19.5...
and 27.5 GHz. Each IF has 8192 channels, resulting in a channel width of 269 kHz, equivalent to 4.1 km s$^{-1}$ at 19.5 GHz or 2.9 km s$^{-1}$ at 27.5 GHz. The observations consisted of approximately 10 h total integration (5 h on-source) with an rms noise level of between 0.01 and 0.03 K.

The follow-up observations were undertaken on 2007 May 3 on the Australia Telescope Compact Array (ATCA) in Director’s time. The correlator setting was FULL, 64 256 64, allowing 0.89 km s$^{-1}$ velocity resolution. The primary beam was 2.3 arcmin and the array configuration was 1.5C, with baselines ranging from 77 to 4500 m providing an angular resolution of $\sim$1 arcsec. The two frequencies were tuned to cover the ammonia (8,6) transition at 20.719 221 GHz and the (11,9) transition at 21.070 739 GHz. These transitions were chosen for ATCA observations as they appeared the brightest of previously undetected ammonia maser transitions in the Mopra spectrum.

The region was observed for $9 \times 20$-min cuts in each transition separated over 5 h. A bright (>1 Jy), close (<5') phase calibrator was observed for 3 min before and after each cut. PKS 1921−293 and PKS 1934−638 were used as the bandpass and primary calibrator, respectively.

The data were reduced using the MIRIAD package. Bad visibilities were flagged, edge channels were removed and the gains/bandpass solutions from the calibrator were applied to the visibilities. The data were Fourier transformed to form image cubes with 0.2-arcsec pixel using natural weighting. The images were CLEANed down to the absolute flux scale are estimated to be $\sim$0.1 mJy beam$^{-1}$. Noise levels were 6 mJy beam$^{-1}$ at the frequency of the (8,6) transition and 3.5 mJy beam$^{-1}$ at the frequency of the (11,9) transition.

3 RESULTS AND DISCUSSION

Fig. 1 shows radio continuum emission contours overlaid on thermal ammonia (4,4) emission (Beuther et al. 2007). The (4,4) emission corresponds well to two millimetre continuum sources I-SMA1 and I-SMA2 (Hunter et al. 2006). We find, in the ATCA observations, that emission in both the (8,6) and (11,9) transitions is unresolved. We consider these to be masers, for reasons given below. Because the emission is unresolved, we do not provide maps of each, but rather show symbols on Fig. 1 to represent the positions of ammonia masers: the (8,6) maser is the cross, the (11,9) maser is the circle and the (6,6) maser is the square (Beuther et al. 2007).

Figure 1. Map of NGC 6334I. The grey-scale shows ammonia (4,4) integrated intensity thermal emission. The two peaks of emission correspond to the millimetre continuum sources (I-SMA1 and I-SMA2) detected by Hunter et al. (2006). The contours represent 8.6-GHz radio continuum emission from the UC H II region (Walsh et al. 1998). The ellipse in the bottom-left corner represents the FWHM beam for the ammonia (4,4) observations. The symbols represent the positions of ammonia masers: the (8,6) maser is the cross, the (11,9) maser is the circle and the (6,6) maser is the square (Beuther et al. 2007).

Figure 2. Spectra for the (11,9) (top) and (8,6) (bottom) masers, as detected by the ATCA. The velocity resolution is 0.89 km s$^{-1}$.

The continuum emission was extracted from a lower-order polynomial fit to line-free channels using UVLIN and images were restored image. Continuum emission was extracted from a lower-order polynomial fit to line-free channels using UVLIN and images were made from these visibilities in the same way. From previous observations of the primary calibrator, PKS 1934−638, errors in the absolute flux scale are estimated to be $\sim$10 per cent. Noise levels were 6 mJy beam$^{-1}$ at the frequency of the (8,6) transition and 3.5 mJy beam$^{-1}$ at the frequency of the (11,9) transition.

\begin{equation}
K = \frac{13.69 \times \lambda^2}{\theta_1 \times \theta_2},
\end{equation}

where $\lambda$ is the observing wavelength in millimetres and $\theta_1$ and $\theta_2$ are the deconvolved major and minor axes in arcseconds, respectively. We find that the (8,6) emission has a deconvolved size of 0.9 $\times$ 0.2 arcsec$^2$ and the (11,9) emission has a deconvolved size of 0.7 $\times$ 0.1 arcsec$^2$. We therefore calculate peak brightness temperatures of $7.8 \times 10^5$ K for the (8,6) transition and $1.2 \times 10^5$ K for the (11,9) emission in the Mopra spectrum. The two peaks of emission correspond to the millimetre continuum sources (I-SMA1 and I-SMA2) detected by Hunter et al. (2006). The contours represent 8.6-GHz radio continuum emission from the UC H II region (Walsh et al. 1998). The ellipse in the bottom-left corner represents the FWHM beam for the ammonia (4,4) observations. The symbols represent the positions of ammonia masers: the (8,6) maser is the cross, the (11,9) maser is the circle and the (6,6) maser is the square (Beuther et al. 2007).

\[ K = \frac{13.69 \times \lambda^2}{\theta_1 \times \theta_2}, \quad (1) \]
transition. If the emission were thermal, it would require a local exciting source with a temperature in excess of these values which we consider extremely unlikely. Thus we interpret the emission in both lines as masers.

Together with the (6,6) transition reported to be masing by Beuther et al. (2007), we have identified three masing transitions of ortho-ammonia. Are there any other transitions of ortho-ammonia that are masing? Our single-dish Mopra observations of NGC 6334I suggest that there may be others. We detect narrow-lined emission in the (7,6), (10,9) and (9,9) transitions, as shown in Fig. 3. Although the strengths of each of these lines are not enough to identify them conclusively as masers, there is some circumstantial evidence that they may well be masers. They all exhibit linewidths less than 3.8 km s\(^{-1}\), which is close to the velocity resolution of the Mopra observations. Indeed, the ATCA observations, with finer velocity resolution, show both the (8,6) and (11,9) lines to have linewidths between 5.8 and 7.3 km s\(^{-1}\), and are clearly resolved in velocity. Apart from their small linewidths, emission in each of these transitions peaks around 5 km s\(^{-1}\), as for the established (6,6), (8,6) and (11,9) masers. This is distinctively different from thermal emission, which peaks between \(-3\) and \(-10\) km s\(^{-1}\). Thermal emission is traced by ammonia (1,1), (2,2) and CH\(_3\)OH (2,0→1,1) (Beuther et al. 2005), as well as ammonia (3,3), (4,4), (5,5) and (6,6) (Beuther et al. 2007). Note that the ammonia (6,6) observations identified both thermal and maser emission components that were clearly separated in velocity.

We note that the Mopra spectrum covers many other lines of ammonia between 19.5 and 27.5 GHz, and whilst some of these lines do show emission, it appears that all others exhibit broader emission features peaking around \(-3\) and \(-10\) km s\(^{-1}\) and so are almost certainly thermal emission. We also note that all the potential masing transitions arise from ortho-ammonia. It is not clear why we do not see any para-ammonia masers in NGC 6334I.

Three methods for creating a population inversion of the ammonia upper levels are through collisional excitation, excitation by infrared radiation or a fortuitous alignment of a molecular transition that allows a \((J, K)\) transition to populate the \((J + 1, K)\) upper level (Madden et al. 1986). It is unlikely that collisional excitation is at work here because extremely high densities \((10^{10} – 10^{12}\) cm\(^{-3}\)) are required. Since we see at least three masing transitions, and perhaps six, it is unlikely that this is due to many lucky alignments of molecular transitions allowing population of the non-metastable states. Therefore we believe that the pumping mechanism for ammonia masers in NGC 6334I must be via infrared photons. This case is strengthened as NGC 6334I is known to be one of the brightest infrared sources in our sky, being intrinsically luminous and relatively nearby (1.7 kpc). This may also explain why these new masers only show thermal emission in other regions.

The detection of new ammonia masers in NGC 6334I indicates that this source is fertile ground for ammonia maser research. Confirmation (or otherwise) of the potential (7,6), (10,9) and (9,9) masers, as well as searching for other non-metastable transitions of ortho-ammonia, may yield more maser detections which will greatly increase the chances of developing theoretical models for ammonia maser pumping, and hopefully will lead to a better understanding of NGC 6334I, which gives rise to these rare masers.

### 4 CONCLUSIONS

We have observed the two non-metastable transitions of ammonia, (8,6) and (11,9), using the ATCA. The (8,6) transition has a peak brightness temperature of \(7.8 \times 10^5\) K, whereas the (11,9) transition has a peak brightness temperature of \(1.2 \times 10^5\) K, indicating that both are masers. The (11,9) transition is \(E_l/k = 1449\) K above ground, making it the highest energy ammonia maser currently known. The position of both masers is consistent with being coincident, to within positional uncertainties, with maser emission in the previously detected (6,6) transition (Beuther et al. 2007).

Single-dish observations of (7,6), (9,9) and (10,9) suggest that they may also be masers based on their small linewidths and overlapping velocity range with the above-mentioned masers, which is distinctly different from the thermal emission systemic velocity. High spatial resolution observations of these transitions are planned to decide whether or not these are masers as well.

### ACKNOWLEDGMENTS

The authors thank Christian Henkel for useful discussions related to this work. We also thank Henrik Beuther for provision of ammonia and continuum data used in this work, and Paul Ho, the referee, who has greatly helped to improve the quality of this work. SNL is supported by a scholarship from the School of Physics at UNSW. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. This research has made use of NASA’s Astrophysics Data System.

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**Figure 3.** Mopra spectra of ammonia transitions suspected to be masing. All spectra exhibit a narrow emission feature between radial velocities 4.9 and 5.9 km s\(^{-1}\). Note that (9,9) emission in the bottom panel exhibits the narrow maser-like feature within this velocity range as well as a broader component at \(-6.7\) km s\(^{-1}\), which is most likely due to thermal emission. The velocity of this thermal component agrees well with velocities derived from other thermal lines. Note also that an unrelated spectral feature appears in the (9,9) spectrum at 51 km s\(^{-1}\). This feature is due to E-type CH\(_3\)OH (\(13_{2,11}–13_{3,12}\)).
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