Shocked molecular hydrogen towards the Tornado nebula

J. S. Lazendic$^{1,2}$, M. Wardle$^3$, M. G. Burton$^4$, F. Yusef-Zadeh$^5$, A. J. Green$^1$ and J. B. Whiteoak$^6$

$^1$ School of Physics A28, University of Sydney, Sydney NSW 2006, Australia
$^2$ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
$^3$ Department of Physics, Macquarie University, N SW 2109, Australia
$^4$ School of Physics, University of New South Wales, Sydney NSW 2052, Australia
$^5$ Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA
$^6$ Australia Telescope National Facility, CSIRO, PO Box 76, Epping NSW 1710, Australia

ABSTRACT

We present near-infrared and millimetre-line observations of the Tornado nebula (G357.7–0.1). We detected 2.12 $\mu$m H$_2$ 1–0 S(1) line emission towards the suspected site of interaction with a molecular cloud revealed by the presence of an OH(1720 MHz) maser. The distribution of the H$_2$ emission is well correlated with the nonthermal radio continuum emission from the Tornado, and the velocity of the H$_2$ emission spans over 100 km s$^{-1}$, which both imply that the H$_2$ emission is shock excited. We also detected millimetre-lines from $^{12}$CO and $^{13}$CO transitions at the velocity of the maser, and mapped the distribution of the molecular cloud in a 2 $\times$ 2 arcmin$^2$ region around the maser. The peak of the molecular cloud aligns well with an indentation in the nebula’s radio continuum distribution, suggesting that the nebula’s shock is being decelerated at this location, which is consistent with the presence of the OH(1720 MHz) maser and shocked H$_2$ emission at that location.

Key words: masers – shock waves – ISM: clouds – ISM: individual: Tornado nebula, G357.7–0.1 - supernova remnants.

1 INTRODUCTION

The inner region of our Galaxy is rich in unusual and unique sources. One such object is the Tornado nebula (G357.7–0.1, MSH 17–39), a peculiar nonthermal source with an axially symmetric morphology. Because of its filamentary structure, steep nonthermal radio spectrum and presence of significant linear polarisation, the Tornado has been classified as a supernova remnant (SNR) (Milne 1979; Clark & Caswell 1976; Shaver et al. 1985a; Stewart et al. 1994). Its elongated and loop-like structure was suggested to be a result of bi-conical flows from the progenitor star (Manchester 1987) or an accreting binary system (Helfand & Becker 1985; Becker & Helfand 1985), but no associated pulsar or neutron star has been found. X-ray emission has been detected from the nebula with the Advanced Satellite for Cosmology and Astrophysics (ASCA) (Yusef-Zadeh et al. 2003) and Chandra X-ray Observatory (Gaensler et al. 2003). Although the emission from the nebula is most probably thermal, deeper observations are needed to unambiguously establish the nature of X-ray emission.

A compact source, called the ‘Eye’ of the Tornado, located about 30 arcsec west from the Tornado, has been linked to the nebula and suggested to be a high proper-motion pulsar associated with the nebula (Shull, Fesen, & Saken 1989). However, the source was found to have a flat radio spectrum suggestive of an HII region (Shaver et al 1985). Most recently, Burton et al. (2004) found 2.16 $\mu$m Br$\gamma$ emission towards the Eye which peaks at a velocity of around $-200$ km s$^{-1}$. These observations imply that the Eye is an isolated core where an embedded massive star is in the process of formation, and it is a foreground object to the Tornado. Hydrogen recombination lines were also detected towards the Eye at radio wavelengths (Brogan & Goss 2003).

OH(1720 MHz) masers have been found at the northwestern tip of the Tornado (Frail et al. 1996; Yusef-Zadeh et al. 1999). When not accompanied by detectable maser emission from the other three OH ground-state transitions at 1612, 1665 and 1667 MHz, the 1720 MHz OH transition is believed to be an indicator of an interaction between SNRs and molecular clouds (e.g. Frail et al. 1996; Green et al. 1997; Lockett, Gauthier & Elitzur 1999; Wardle 1999; Wardle & Yusef-Zadeh 2002). The maser in the Tornado has a velocity of $-12.4$ km s$^{-1}$, and if its distance is assumed to be more than a few hundred parsec (avoiding the distance ambiguity), a dis
tance of 11.8 kpc is derived from the Galactic rotation curve [Fich, Blitz, & Stark 1990]. This is consistent with 21-cm H1 absorption against the Tornado, which places the nebula at a distance greater than 5 kpc (Radhakrishnan et al. 1972). The magnetic field strength towards the OH(1720 MHz) maser, determined from measurements of OH-line Zeeman splitting, is 0.7 mG (Brogan et al. 2001).

We obtained near-infrared (NIR) and millimetre-line observations towards the northwestern part of the Tornado to investigate the implied interaction of the nebula and the surrounding molecular gas. We also obtained archival radio continuum data at 20 cm for a comparison. The observations are described in Section 2 and the results are given in Section 3. The results are discussed in Section 4 and summarized in Section 5.

2 DATA

2.1 UNSWIRF observations

For NIR observations of the Tornado we used the University of New South Wales Fabry-Perot narrow-band tunable filter (UNSWIRF; Ryder et al. 1998) mounted on the 3.9-m Anglo-Australian Telescope during June 1999. The observations were centred near the location of the OH(1720 MHz) maser in the nebula at RA(1950) = 17h 36m 55s, Dec.(1950) = −30◦ 56′ 1′′. Only a small part of the Tornado was covered because the UNSWIRF aperture had a circular image of 100 arcsec in diameter with a pixel size of 0.77 arcsec. The UNSWIRF field of view is marked with a circle in Figure 1. Five frames at different Fabry-Perot settings were obtained in the 2.12 µm H2 1−0 S(1) line, equally spaced by 40 km s−1 and centred on the maser velocity. The velocity resolution of the instrument was ≈ 75 km s−1. The integration time was 180 seconds per frame. For the continuum subtraction, an additional frame was taken at a velocity setting of −400 km s−1 from the first frame. A velocity cube, constructed from the five frames, is fitted with the instrumental Lorentzian profile to determine the H2 line parameters across the field. The H2 line flux density and line centre velocity are determined to within ≈ 30 per cent and ≈ 20 km s−1, respectively. The intensity was calibrated using additional observations of the standard star BS 8658. To establish the coordinate scale for the UNSWIRF image, we used the BS 8658. To establish the coordinate scale for the UNSWIRF calibrated using additional observations of the standard star.

2.2 SEST observations

We used the 15-m Swedish-ESO Submillimeter Telescope (SEST) during June 2000 to observe the region towards the OH(1720 MHz) maser in 12CO, 13CO, CS, HCO+, HCN and H2CO transitions between 1.3 and 3 mm. Table 1 lists the observed molecular transitions, frequencies and corresponding telescope beam widths. The spectral resolution ranged between ≈ 0.1 km s−1 at 1.3 mm and ≈ 0.3 km s−1 at 3 mm. The observations were performed in position-switching mode with reference position at RA(1950) = 17h 47m 10s, Dec.(1950) = −32◦ 43′ 00″. The two 12CO transitions were obtained over a 2 × 2 arcmin2 region centred at RA(1950) = 17h 36m 54s, Dec.(1950) = −30◦ 56′ 25″, with a 20 arcsec grid and 30 second integration per position. For the other molecular transitions, observations were taken in a five-point-cross grid centred at RA(1950) = 17h 36m 54s, Dec.(1950) = −30◦ 56′ 05″, plus 20 arcsec offset. The integration times were 60 seconds for the 12CO and 13CO transitions and 180 seconds for all the other transitions.

Telescope pointing accuracy to better than 5 arcsec was maintained using periodic observations of the SiO masers associated with AH Sco and W Hyd. The data have been corrected on-line for atmospheric absorption by periodic observations of a blackbody calibration source. After baseline subtraction and Hanning smoothing, the data were scaled to main-beam brightness temperature (Tmb) using the main-beam efficiencies (0.74, 0.70, 0.67 and 0.45 at 85–100 GHz, 100–115 GHz, 130–150 GHz and 220–265 GHz respectively).

2.3 VLA data

The radio continuum data were obtained from archives of the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO). The observations of the Tornado nebula were carried out on 28 April 1991 and 13 December 1985 at 20 cm in its A and D-array configurations, respectively. Standard calibration of both data sets used 1748–253 and 3C286 as the phase and amplitude calibrators, respectively. Standard self-calibration was also applied to both data sets before the final image was constructed using the Maximum Entropy method (MEM in AIPS).

3 RESULTS AND ANALYSIS

The 20 cm radio image of Tornado, shown in Figure 1, has a resolution of 2.65′′ × 1.07′′ (PA=−6.7◦). The image illustrates nebula’s filamentary structure and we indicate the main features – the bright western region is called the ‘Head’, which is followed by a prominent arc in the centre of the nebula and faint filaments comprising the ‘Tail’ of the nebula. The compact source near the nebula, the Eye of the Tornado, is also indicated.

3.1 H2 emission

We have detected for the first time H2 line emission towards the Tornado. Figure 2 shows contours of the velocity-integrated 2.12 µm H2 1–0 S(1) line emission overlaid on a greyscale image of the 2MASS K-band (2.15µm). The emission is ring-shaped with a diameter of ≈ 50 arcsec, and contains a number of peaks. The emission peaks are 5–10 arcsec in size. The peak flux density of the 2.12 µm H2 1–0 S(1) line emission is 1.4×10−4 erg s−1 cm−2 sr−1 and the 3σ rms noise is 8×10−5 erg s−1 cm−2 sr−1; the integrated flux density of the whole source is 2.4×10−12 erg s−1 cm−2. After correcting for an assumed extinction in K-band of at least AK ≈ 3 (since the object is behind the Galactic centre), the peak flux density of the 2.12 µm H2 1–0 S(1) line emission is 2×10−5 erg s−1 cm−2 sr−1, the integrated flux density is

1 see http://spider.ipac.caltech.edu/staff/hlm/2mass/calvsuc/calvsuc.html
3.8 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$, and the 2.12\text{	extmu}m H$_2$ luminosity is 167$L_\odot$ for distance of 11.8 kpc.

The H$_2$ line centre velocities, marked in Figure 2, span over $\sim 100$ km s$^{-1}$ across the emission region. There are 7 identifiable clumps, with velocities ranging from $-95$ to $+25$ km s$^{-1}$, with the mean velocity around $-54$ km s$^{-1}$. They range from 40 km s$^{-1}$ blue of the mean to 70 km s$^{-1}$ red of the mean. Apart from the clump at $+26$ km s$^{-1}$, however, they are all blue-shifted from the velocity of the cloud, as determined by the CO and OH maser emission. The emission at positive velocities appears as a knot located at the south-eastern region. Unfortunately, this component was not observed with sufficient Fabry-Perot spacings to infer the red-shifted extent of its emission.

### 3.2 CO emission

Several $^{12}$CO and $^{13}$CO emission components at different velocities were detected along the line of sight to the Tornado nebula. Some of the features can be seen in Figure 3, which shows the $^{12}$CO 1–0 spectrum towards the position of the OH(1720 MHz) maser in the range $-40$ to $+15$ km s$^{-1}$. In Figure 4, we show the individual $^{12}$CO 2–1 spectra across a 2 x 2 arcmin$^2$ region of the Tornado’s Head. The (0,+20) position corresponds to the location of the OH(1720 MHz) maser. Similarly, Figure 5 shows the five $^{13}$CO 2–1 spectra, where the (0,0) position corresponds to the location of the OH(1720 MHz) maser. We have assumed that the molecular cloud associated with the Tornado nebula has a velocity close to the maser velocity ($-12.4$ km s$^{-1}$), and the spectrum shows a CO feature near $-12$ km s$^{-1}$ with a linewidth of $\sim 4$ km s$^{-1}$. The spectral features were fitted with Gaussian profiles and the resulting line parameters for the cloud associated with the nebula are summarised in Table 1. In contrast to the $^{12}$CO and $^{13}$CO transitions, the other molecular transitions were found to be very weak, providing only upper limits (Table A1). We found no significant line broadening ($\geq 10$ km s$^{-1}$) in the present data which would provide a clear kinematic evidence of shock interaction.

The measured line ratio $R = T_{mb}^{12}$CO/$T_{mb}^{13}$CO was $\approx 3.4$ for the 1–0 transitions, and $\approx 3.0$ for the 2–1 transitions, which implies that the $^{12}$CO emission is optically thick. Adopting an overall isotope ratio $R_I = [^{12}$CO]/[^{13}$CO] = 50 ± 20 (e.g., Langer & Penzias 1990), we estimate an upper limit on the $^{12}$CO optical depth of $\tau \approx R_I/R \approx 21$ for the 1–0 line. Since $^{12}$CO is optically thick, the actual $^{12}$CO 1–0/2–1 line ratio should be close to unity. Thus, by equating the two brightness temperature of the two $^{12}$CO lines, we derived a beam-deconvolved source size of $\approx 40$ arcsec. We can then calculate the actual brightness temperatures corrected for the source size from $T_S = T_{mb}(1 + \Omega_B/\Omega_S)$, where $\Omega_B$ and $\Omega_S$ are the beam and source solid angles, respectively (e.g., Jansen, van Dishoeck & Black 1994; Roblfs & Wilson 1996). For the two $^{12}$CO transitions we then have $T_S(1-0) = 20$ K and $T_S(2-1) = 14$ K.

To determine the temperature of the molecular gas towards the $^{12}$CO peak, we used the molecular-line excitation code with the mean escape probability (MEP) (for details see e.g., Jansen et al. 1994). Our excitation modeling of the two $^{12}$CO lines implies a kinetic temperature of 20 ± 5 K for a gas density of $10^4$–$10^6$ cm$^{-3}$. This is consistent with the fact that for an optically thick $^{12}$CO the gas temperature should be similar to the brightness temperature of the $^{12}$CO lower-energy transitions. We also estimate $^{12}$CO column density of $N(^{12}$CO) $\approx (1-8) \times 10^{17}$ cm$^{-2}$ from our modeling. Using the standard fractional abundance $[^{12}$CO]/[H$_2$] of 10$^{-4}$ (e.g., Irvine, Goldsmith, & Hjalmarson 1987; van Dishoeck, Jansen, & Phillips 1993) we derive $N$(H$_2$) $\approx (1-8) \times 10^{21}$ cm$^{-2}$. The upper limit of the $^{13}$CO optical depth is 24/70 = 0.3, and column density is $2.7 \times 10^{18}$ cm$^{-2}$. Because of the non-detection of molecules with larger dipole moments (e.g., CS), we do not have a more reliable method to constrain the density of the molecular gas.

A velocity-integrated map of $^{12}$CO 2–1 emission between $-10$ and $-16$ km s$^{-1}$ is shown in Figure 5. Since the optical depths are large, the observed $^{12}$CO distribution traces the temperature distribution rather than the column density distribution.

### 4 DISCUSSION

H$_2$ emission has been studied in only a few of the known SNR masers, such as IC 443 (Burton et al. 1988), Ser A East (Yusef-Zadeh et al. 2001) and G359.1–0.5 (Lazendic et al. 2002). The line ratio of the H$_2$ 1–0 and 2–1 S(1) transitions may be used to establish the excitation mechanism for H$_2$ emission. Unfortunately, we were unable to obtain 2–1 S(1) observations towards the Tornado, but we argue on the basis of morphology and kinematics that the H$_2$ emission detected towards the OH(1720 MHz) maser in the Tornado nebula is shock excited, as found in other SNR associated with OH(1720 MHz) emission (e.g., Burton et al. 1988; Lazendic et al. 2002, 2004). In Figure 7 we compare the integrated 2.12 \text{	extmu}m H$_2$ 1–0 S(1) line emission with the 20 cm radio continuum emission. In the region where the SNR encounters a dense molecular cloud the SNR shock will be decelerated, producing enhanced radio emission due to strong shock compression and enhanced particle acceleration. Both the H$_2$ and radio continuum emission features have filamentary morphology, and there is a good correlation between the H$_2$ and radio continuum maxima; we interpret this agreement as an indication of physical association. The bright clumps in the H$_2$ emission represent small-scale structures in the inhomogeneous ambient medium, illuminated by the SNR shock (see e.g., Burton et al. 1988). Another argument for shock excitation is the significant velocity motion in the H$_2$ emitting gas across the region, which is opposite to that found in fluorescent sources where velocities are essentially at the ambient velocity of the molecular cloud (Burton, Hollenbach, & Tielens 1990). The H$_2$ emission is also spatially coincident with extended OH(1720 MHz) emission found towards the nebula (Yusef-Zadeh et al. 1994), which is believed to be evidence of large-scale interactions between a SNR and an adjacent molecular cloud.

The molecular cloud associated with the nebula and the OH(1720 MHz) maser is optically thick, with a kinetic temperature of $\approx 20$ K, assuming a gas density of $10^4$–$10^6$ cm$^{-3}$. This temperature and density are in agreement with properties expected for the molecular cloud interacting with SNRs associated with OH(1720 MHz) masers (Lockett et al. 1999), which suggests that we are detecting
mostly the pre-shock molecular gas. We did not detect the broad line profiles from the warm post-shock region, like those seen in IC 443 (van Dishoeck et al. 1992). The 50 arcsec diameter of the H$_2$ ring is comparable to the 45 arcsec beam size at the 12CO 1–0 frequency, and we might expect to detect the warm shocked gas. Indeed, the location of the OH(1720 MHz) maser within the CO peak contour in Figure 6 indicates that we might detect contribution from both the pre-shock and post-shock gas. However, the molecular gas is optically thick and we might be probing only the cool envelope of the cloud with the observations of the 12CO transitions. Furthermore, weaker broad wings from the warm gas might be confused with neighbouring molecular features. Similar observations of shocked molecular gas towards other SNR-cloud intersections imply that the broad emission component is usually stronger in higher 12CO transitions (e.g., Seta et al. 1998), or restricted to a small molecular clumps (e.g., Reach et al. 2002). Thus, observations of higher energy transitions (which would also result in higher spatial resolution) might be needed to detected the shocked molecular gas in the millimetre band. Indeed, preliminary results from observations of CO 4–3 line show broad line emission centered at −12 km s$^{-1}$ (Yusef-Zadeh et al. 2004, in preparation).

Figure 6 shows the integrated 12CO 2–1 line emission superimposed on the 20 cm radio continuum emission. The blast wave delineated by the radio emission is indented at the location of the OH(1720 MHz) maser and the 12CO peak, suggesting that the molecular cloud is large and dense enough to cause a significant impediment to the shock front. This resembles the well known case of SNR-cloud interaction seen in the Cygnus Loop (e.g., Danforth, Blair & Raymond 2001). Also, the western side of the H$_2$ emission appears more flattened compared to the other parts, which is suggestive of a compression resulting from the interaction between the nebula and the surrounding molecular gas. Thus, the OH(1720 MHz) maser, the H$_2$ emission and the radio continuum indentation is the indication that the blast wave has just begun to interact with the tip of the molecular cloud. The distribution of molecular gas components is consistent with the OH(1720 MHz) maser being located in a post-shock layer just behind a shock front, oriented transverse to the line of sight, as predicted by the theory for OH(1720 MHz) maser formation (Elitzur 1976, Lockett et al. 1999). Furthermore, the X-ray flux observed from the Tornado (Gaensler et al. 2003) is consistent with that required to produce the necessary OH (Wardle 1999).

The OH(1720 MHz) maser is located at the western edge of the H$_2$ emission and its velocity (−12 km s$^{-1}$) differs significantly from the mean velocity of H$_2$ emission. This is not too surprising because we see masers only at the location where the shock is propagating perpendicular to our line of sight (Lockett et al. 1999), whereas we see H$_2$ emission from any location in the shocked gas. The extended maser emission spans over a larger velocity gradient between −13.1 and −8.7 km s$^{-1}$ (Yusef-Zadeh et al. 1999). It is expected that the shock associated with extended maser emission is not exactly perpendicular to the line of sight, although these velocities are still much lower than the mean velocity of H$_2$ emission. The large velocity span of H$_2$ emission features is probably the result of seeing a shock under different angles. Although H$_2$ emission appears ring-like, the distribution of H$_2$ line-velocities, when compared to −12 km s$^{-1}$ as a reference, is clearly incompatible with any expansion of a ring. In fact, it may be simply a chance line of sight projection that is causing the apparent ring structure. Presumably the north-west structure of the H$_2$ ring is marking the shock front as it runs into the CO cloud, given the position offset between the CO and H$_2$ in Figure 6. The rest of the H$_2$ ring is probably not a continuous structure but foreground or background structure being shocked with a different shock velocity vector. This is supported by the fact that there is no coherence between two adjacent clumps at different velocities when we examine the H$_2$ cube, and velocities jump from one clump to the other, supporting the notion that clumps are distinct features. If we suppose the greatest shock speed is $V_{max}$, running in to the lowest density molecular gas, $n_{min}$, then the line of sight velocity we measure is $V = V_{max}(n_{min}/n)^{0.5}(\cos \theta)$, where the velocity $V$ is with respect to the −12 km s$^{-1}$ ambient cloud value, with $\theta = 90^\circ$ being the plane of the sky, and $n$ is the density at that point. In general the velocities get more negative towards the rear of the ring, which implies that $\theta$ is small here so the shock is moving nearly directly towards us to the rear of the H$_2$ ring.

5 SUMMARY

We have detected 2.12 µm H$_2$ 1–0 S(1) emission towards the northwestern edge of the Tornado nebula. The emission has a ring-like morphology and encompasses the location of the OH(1720 MHz) maser. The correlation between the radio continuum and H$_2$ emission, and significant velocity motions suggest that the H$_2$ emission originates from an expansion of the shock wave and is most probably shock excited. The OH(1720 MHz) maser is located at the western edge of the H$_2$ emission, which probably delineates the leading edge of shock front.

Molecular transitions of 12CO and 13CO were also detected at the maser velocity of −12 km s$^{-1}$; emission from CS, HCO$^+$, HCN and H$_2$CO was not detected. The millimetre-line observations were found to probe only the ambient molecular gas associated with the nebula, which is optically thick and warm ($\approx 20$ K, for assumed gas density of $10^2$–$10^5$ cm$^{-3}$). The location of the molecular gas coincides with an indentation in the radio continuum distribution and the OH(1720 MHz) maser position, suggesting that the molecular cloud is large enough to cause significant deceleration of the blast wave shock. Observations of optically thinner higher transitions of 12CO are needed to examine the properties of shocked part of the molecular gas.

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REFERENCES

Brogan, C. L. & Goss, W. M. 2003, AJ, 125, 272
Becker, R. H. & Helfand, D. J. 1985, Nature, 313, 115
Brogan, C. L., Frail, D. A., Goss, W. M., & Troland, T. H. 2000, ApJ, 537, 875
Burton, M. G., Geballe, T. R., Brand, P. W. J. L., & Webster, A. S. 1988, MNRAS, 231, 617
Burton, M. G., Hollenbach, D. J., & Tielens, A. G. G. M. 1990, ApJ, 365, 620
Burton, M. G., Lazendic, J. S., Yusef-Zadeh, F., & Wardle, M. 2004, MNRAS, 348, 638
Caswell, J. L., Haynes, R. F., Milne, D. K., & Wellington, K. J. 1980, MNRAS, 214, 617
Clark, D. H. & Caswell, J. L. 1976, MNRAS, 174, 267
Cutri, R. M. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garzón et al. (Dordrecht: Kluwer), 187
Danforth, C. W., Blair, W. P., & Raymond, J. C. 2001, AJ, 122, 938
Elitzur, M. 1976, ApJ, 203, 124
Gaensler, B. M., Fomalont, E. J., Slane, P. O., Miller, J. M., Wijnands, R., Einchenber, S. S., & Lewin, W. H. G. 2003, ApJL, L53
Fich, M., Blitz, L., & Stark, A. A. 1989, ApJ, 342, 272
Frail, D. A., Goss, W. M., Reynoso, E. M., Giacani, E. B., Green, A. J., & Otrupcek, R. 1996, AJ, 111, 1651
Green, A. J., Frail, D. A., Goss, W. M., & Otrupcek, R. 1997, AJ, 114, 2058
Helfand, D. J. & Becker, R. H. 1985, Nature, 313, 118
Irvine, W. M., Goldsmith, P. F., & Hjalmarson, A. 1987, ASSL Vol. 134: Interstellar Processes, 561
Jansen, D. J., van Dishoeck, E. F. & Black, J. H. 1994, A&A, 282, 605
Langer, W. D. & Penzias, A. A. 1990, ApJ, 357, 477
Lazendic, J. S., Wardle, M., Burton, M. G., Yusef-Zadeh, F., Whiteoak, J. B., Green, A. J., & Ashley, M. C. B. 2002, MNRAS, 331, 537
Lazendic, J. S., Wardle, M., Whiteoak, J. B., Burton, M. G. & Green, A. J., 2004, to be submitted to MNRAS
Lockett, P., Gauthier, E. & Elitzur, M. 1999, ApJ, 511, 235
Manchester, R. N. 1987, A&A, 171, 205
Milne, D. K. 1979, Australian Journal of Physics, 32, 83
Radhakrishnan, V., Goss, W. M., Murray, J. D., & Brooks, J. W. 1972, ApJS, 24, 49
Reach, W. T., Rho, J., Jarrett, T. H., & Lagage, P. 2002, ApJ, 564, 302
Rohlfs, K. & Wilson, T. L. 1996, Tools of Radio Astronomy, Springer-Verlag, Berlin
Ryder, S. D., Sun, Y.-S., Ashley, M. C. B., Burton, M. G., Allen, L. E. & Storey, J. W. V. 1998, Publications of the Astronomical Society of Australia, 15, 228
Seta, M. et al. 1998, ApJ, 505, 286
Shaver, P. A., Salter, C. J., Patnaik, A. R., van Gorkom, J. H., & Hunt, G. C. 1985, Nature, 313, 113
Shaver, P. A., Pottasch, S. R., Salter, C. J., Patnaik, A. R., van Gorkom, J. H., & Hunt, G. C. 1985, A&A, 147, L23
Shull, J. M., Fesen, R. A., & Saken, J. M. 1989, ApJ, 346, 860
Stewart, R. T., Haynes, R. F., Gray, A. D., & Reich, W. 1994, ApJL, 432, L39
van Dishoeck, E. F., Jansen, D. J., & Phillips, T. G. 1993, A&A, 279, 541
Wardle, M. 1999, ApJL, 525, L101
Wardle, M. & Yusef-Zadeh, F. 2002, Science, 296, 2350
Yusef-Zadeh, F., Goss, W. M., Roberts, D. A., Robinson, B., & Frail, D. A. 1999, ApJ, 527, 172
Yusef-Zadeh, F., Stolovy, S. R., Burton, M., Wardle, M., & Ashley, M. C. B. 2001, ApJ, 560, 749
Yusef-Zadeh, F., Wardle, M., Rho, J., & Sakano, M. 2003, ApJ, 585, 319

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Table 1. Molecular lines observed towards the Tornado nebula at RA(1950) = $17^\text{h} 36^\text{m} 54^\text{s}$, Dec.(1950) = $-30^\circ 56^\prime 05^\prime\prime$. The first three columns list the molecular transitions and their frequencies. The fourth column lists the SEST beam sizes (FWHM), and the last three columns give the spectral-line parameters: main-beam brightness temperature ($T_{\text{mb}}$) and rms noise (upper limits are 2σ values), central velocity ($V_{\text{LSR}}$) and line width ($\Delta V_{\text{LSR}}$).

| Molecule | Transition | $\nu$ (GHz) | Beam Size (arcsec) | $T_{\text{mb}}$ (K) | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V_{\text{LSR}}$ (km s$^{-1}$) |
|----------|------------|-------------|--------------------|---------------------|-----------------------------|----------------------------------|
| $^{12}\text{CO}$ | 2–1 | 230.538 | 23 | 10.5±0.3 | $-11.0$ | 4.0 |
| | 1–0 | 115.271 | 45 | 8.6±0.4 | $-11.2$ | 5.1 |
| $^{13}\text{CO}$ | 2–1 | 220.399 | 23 | 3.5±0.2 | $-11.0$ | 3.7 |
| | 1–0 | 110.201 | 45 | 2.5±0.1 | $-11.1$ | 3.7 |
| CS | 3–2 | 146.969 | 34 | <0.1 | – | – |
| | 2–1 | 97.981 | 52 | <0.2 | – | – |
| HCO$^+$ | 1–0 | 89.188 | 54 | <0.2 | – | – |
| HCN | 1–0 | 88.632 | 55 | <0.1 | – | – |
| H$_2$CO | $3(2,2)$–$2(2,1)$ | 218.475 | 23 | <0.1 | – | – |
| | $3(0,3)$–$2(0,2)$ | 218.222 | 24 | <0.1 | – | – |
**Figure 1.** 20 cm Very Large Array image of the Tornado nebula with the main features labelled. The cross marks the location of the OH(1720 MHz) maser and the circle marks the field of view of the UNSWIRF aperture (see Section 2.1).

**Figure 2.** Contours of the velocity-integrated 2.12 µm H$_2$ 1–0 S(1) line emission towards the OH(1720 MHz) maser in the Tornado nebula, overlaid on the 2MASS K-band greyscale image matching the size of the UNSWIRF field of view. The contours are: 1.6, 4.7, 6.3, 7.9, 9.5, 11.1, 12.6, 14.2 x10$^{-5}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The white cross marks the location (and the velocity) of the OH(1720 MHz) maser. Labelled are also the line centre velocities (in km s$^{-1}$) of prominent features.
Figure 3. $^{12}$CO 1–0 spectrum observed towards the OH(1720 MHz) maser in the Tornado nebula in the range $-40$ to $+15$ km s$^{-1}$ demonstrates spectral features along the line of sight.

Figure 4. $^{12}$CO 2–1 spectra taken over $2' \times 2'$ region towards the OH(1720 MHz) maser in the Tornado nebula. The (0,0) position is at RA(1950) = 17$^h$ 36$m$ 54$s$, Dec.(1950) = $-30^\circ$ 56' 25'', and the spectrum closest to the OH(1720 MHz) masers position is marked with a star. The scale is given in the panel in the upper right; the velocity and temperature scales are given in K and km s$^{-1}$, respectively.
Figure 5. $^{13}$CO 2–1 spectra taken over $2' \times 2'$ region towards the OH(1720 MHz) maser in the Tornado nebula. The (0,0) position is at RA(1950) = 17$^h$ 36$^m$ 54$^s$, Dec.(1950) = $-30^\circ$ 56' 05", and the spectrum closest to the OH(1720 MHz) masers position is marked with a star. The scale is given in the upper panel; the velocity and temperature scales are given in K and km s$^{-1}$, respectively.

Figure 6. Integrated $^{12}$CO 2–1 emission towards OH(1720 MHz) maser in the Tornado. The contours are: 8, 11, 14, 17, 22 and 25 K km s$^{-1}$. The cross marks the location of the OH(1720 MHz) maser.
Figure 7. Contours of H$_2$ 1–0 S(1) line emission superimposed on the 20 cm VLA grayscale image. The contour levels are 1.6, 6.3 and $9.5 \times 10^{-5}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The cross marks the location of the OH(1720 MHz) maser.

Figure 8. Contours of the $^{12}$CO 2–1 line emission overlaid on (a) the 20 cm greyscale VLA image and (b) the velocity-integrated 2.12 µm H$_2$ 1–0 S(1) line emission in the Tornado nebula. The $^{12}$CO contours are the same as in Figure 7. The cross marks the location of the OH(1720 MHz) maser.