Multiwavelength observations of the supernova remnant G349.7+0.2 interacting with a molecular cloud

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ABSTRACT
We present molecular-line observations at millimetre, centimetre and infrared wavelengths of the region containing OH(1720 MHz) masers in the supernova remnant (SNR) G349.7+0.2, using the Australia Telescope (AT) Mopra antenna, the Swedish–ESO Submillimeter Telescope, the AT Compact Array and the UNSW Infrared Fabry–Perot narrow-band filter installed on the Anglo-Australian Telescope. Several molecular transitions were observed between 1.6 and 3 mm to constrain the physical parameters of the molecular cloud interacting with the SNR and to investigate the effects of the SNR shock on the gas chemistry. We detected shock-excited near-infrared H$_2$ emission towards the centre of the SNR, revealing highly clumped molecular gas and a good correlation with published mid-infrared images from the Spitzer Space Telescope. An excellent correlation between the H$_2$ clumps and OH(1720 MHz) maser positions supports the shock excitation of the OH(1720 MHz) maser emission. Furthermore, we detected OH absorption at 1665 and 1667 MHz which shows a good correlation with the shocked H$_2$ emission and the masers. We found maser emission at 1665 MHz near the OH(1720 MHz) masers in this SNR, which is found to be associated with a GLIMPSE source SSTGLMC G349.7294+00.1747. We also detected 1665 and 1667 MHz OH masers, and weak 4.8 GHz H$_2$CO absorption towards the ultracompact H II region IRAS 17147−3725 located to the southeast of the SNR. We found no 4.7- or 6-GHz excited-state OH masers or 6-GHz CH$_3$OH maser towards either the SNR or the H II region.

Key words: masers – shock waves – ISM: individual objects: G349.7+0.2 – ISM: individual objects: IRAS 17147−3725 – ISM: supernova remnants – infrared: ISM.

1 INTRODUCTION
The young, massive stars which are progenitors of supernova remnants (SNRs) live only a relatively short time (a few million years) and do not move far from the molecular clouds from which they are born. Hence it is expected that SNRs formed from such massive stars should be found in close proximity to their parent molecular clouds. The shocks driven by SNRs into dense molecular clouds compress, accelerate and heat the gas. They can partially or completely disrupt the clouds and may initiate star formation by triggering further gravitational collapse following the cooling of the compressed gas. The shocks also provide energy which can potentially excite higher molecular transitions and activate chemical reactions forbidden in cold molecular clouds, changing the chemical abundances in the cloud. Thus, observations of molecular clouds which have interacted with a supernova blast wave can provide important information about the physical and chemical processes associated with the shocks.

For many years, the best unambiguous case of an SNR-molecular cloud interaction was the object IC 443, where broadened molecular lines (see DeNoyer 1979; van Dishoeck, Jansen & Phillips 1993, and references therein) and shocked molecular hydrogen (Burton et al. 1988) were detected. However, recent detections of OH(1720 MHz) maser emission near the boundary regions of ∼10 per cent of the Galactic SNRs (Frail, Goss & Slysh 1994; Frail et al. 1996; Yusef-Zadeh et al. 1996; Green et al. 1997; Koralesky et al. 1998) have become signposts of the SNR interaction with molecular clouds. This maser emission, usually unaccompanied by maser emission in the other three ground-state transitions, is excited from OH collisions with H$_2$ molecules in a gas with temperatures...
between 50–125 K, a density of \(-10^4\) cm\(^{-3}\) and an OH column density between \(10^{15}\) and \(10^{17}\) cm\(^{-2}\) (Elitzur 1976; Lockett, Gauthier & Elitzur 1999). These conditions can be found in cooling gas behind a non-dissociative C shock, irradiated by the X-ray flux from the SNR interior (Wardle 1999). Hence, SNRs associated with this maser emission are good candidates for studies of shock phenomena in molecular clouds. Follow-up molecular-line observations of these SNRs have confirmed the presence of shocked molecular gas towards the OH(1720 MHz) maser locations (e.g. Frail & Mitchell 1998; Reach & Rho 1999, 2000; Lazendic et al. 2002; Reach et al. 2002; Lazendic et al. 2004; Reach, Rho & Jarrett 2005; Reach et al. 2006). Furthermore, new observations with improved sensitivity raised the fraction of maser-emitting SNRs to 15 per cent, implying that this fraction might become even higher with deeper searches for OH(1720 MHz) masers (Hewitt & Yusef-Zadeh 2009).

One of the SNRs associated with OH(1720 MHz) maser emission is G349.7+0.2. This is the third brightest Galactic SNR at radio wavelengths, after Cas A and the Crab nebula (Shaver et al. 1985). It is classified as a shell-type remnant from the radio continuum image, which has a circular shape (~2.5 arcmin in diameter) with a bright periphery, and a typical spectral index of ~0.5. However, it has a southern enhancement that is different from the morphology of typical shell SNRs. Five OH(1720 MHz) masers have been detected along the bright emission ridge of the SNR (Franl et al. 1996) with radial local standard of rest (LSR) velocities ranging from 14.3 to 16.9 km s\(^{-1}\). Their properties are listed in Table 1. A magnetic field with a strength of 0.35 \(\pm\) 0.05 mG has been measured towards the brightest of the masers (Brogan et al. 2000). The distance to the SNR estimated to be 18.3 \(\pm\) 4.6 kpc from H\(^1\) absorption measurements (Caswell et al. 1975), and the maser velocities are consistent with this value (~22 kpc; Frail et al. 1996). The SNR is predicted to be \(~3000\) yr old and its X-ray morphology is strikingly similar to the radio morphology (Lazendic et al. 2005), suggestive of expansion into a medium with a large density gradient, as has been observed in the \(^1\)CO 1–0 line by Reynoso & Mangum (2001), with a resolution of 54 arcsec. Dubner et al. (2004) observed \(^13\)CO1–0, 2–1 and 3–2 lines towards the central part of the SNR and the location of OH masers, and found the line ratios indicative of shocked molecular gas.

To investigate the effects of SNR shocks on interstellar molecular gas and to test the models for the generation of OH(1720 MHz) emission via shocks, we carried out molecular-line observations in both radio and infrared bands. We used observations of molecular hydrogen to trace recently shocked gas identified by the presence of the masers. Molecular lines at millimetre wavelengths were used to probe the structure, dynamics and composition of the molecular gas in which masers are created. OH line observations at centimetre wavelengths (1665 and 1667 MHz) were used to derive OH column densities and to test the model for OH(1720 MHz) maser production. We also searched for excited-state OH maser emission at 4.7 and 6.0 GHz, CH\(_3\)OH maser emission at 6 GHz, and H\(_2\)CO absorption at 4.8 GHz. We summarize the observations in Section 2 and present the results in Section 3. The results are discussed in Section 4, and our conclusions are given in Section 5.

## 2 Observations

### 2.1 Molecular-line observations at mm wavelengths

To obtain the extent of the molecular cloud associated with G349.7+0.2 we used the 22-m Australia Telescope Mopra antenna during 1998 October. Observations of the 3-mm 1–0 transition of \(^13\)CO were undertaken on a \(7 \times 7\) point grid centred at RA (2000) = \(17^\text{h}18^\text{m}00^\text{s}\), Dec. (2000) = \(-37^\circ26'10''\), with a 30 arcsec grid and 60-s integration per position. For observations of other molecular species (\(^12\)CO, CS, HCO\(^+\), HCN, H\(_2\)CO, SiO and SO) we used the 15-m Swedish–ESO Submillimetre Telescope (SEST) telescope in 1999 February and June. The observed transitions, their frequencies and corresponding beamwidths are given in Table 2. Most of the transitions were observed over a \(2 \times 2.5\) arcmin\(^2\) region centred at RA (2000) = \(17^\text{h}18^\text{m}00^\text{s}\), Dec. (2000) = \(-37^\circ26'30''\), with a 24 arcsec grid spacing and 60-s integration per position. Due to the overall weak emission of the CS, H\(_2\)CO, SO and SiO lower energy transitions, higher transitions for these species were observed only at the maser positions in a five-point cross grid with 20-arcsec offset. For all transitions a position-switching observing mode was used with a reference position at RA (2000) = \(17^\text{h}13^\text{m}23^\text{s}\), Dec. (2000) = \(-37^\circ03'30''\).

When the \(^13\)CO observations at 110 GHz were carried out with the Mopra telescope, the effective diameter of the dish was 15 m with a corresponding beamwidth of about 43 arcsec, slightly smaller than the SEST beamwidth of about 45 arcsec for the 115-GHz \(^12\)CO observations. For the Mopra observations, the attenuation due to atmospheric absorption was corrected using measurements of a blackbody paddle at ambient temperature (see Hunt Cunningham et al. 2003, for more details). The corrected intensities were then matched to the main-beam temperature scale of the SEST by observing the molecular cloud in the direction of the Ori A SiO maser and scaling the observed intensities to their SEST counterparts. The final intensity calibration is believed to be accurate to within 15 per cent. The SEST observations were similarly corrected for atmospheric attenuation during the observations, and then corrected for the main-beam efficiency (0.74, 0.70, 0.67 and 0.45 at 85–100, 100–115, 130–150 and 220–265 GHz, respectively). For both telescopes the pointing was corrected approximately every 2 h by observations of the 86-GHz SiO masers of AH Sco and W Hyd.

### Table 1. The OH(1720 MHz) masers detected towards the SNR G349.7+0.2 (from Frail et al. 1996). Given are maser designations, as used in this paper, positions, peak flux density (\(S_p\)), peak velocity (\(V_{\text{LSR}}\)) and velocity resolution (\(\Delta v\)).

| Designation | RA (2000) | Dec. (2000) | \(S_p\) (mJy) | \(V_{\text{LSR}}\) (km s\(^{-1}\)) | \(\Delta v\) (km s\(^{-1}\)) |
|-------------|------------|-------------|----------------|-----------------|----------------|
| M1          | 17 17 59.2 | -37 26 21.07 | 90             | +16.7           | 1.5            |
| M2          | 17 17 59.2 | -37 26 48.07 | 152            | +14.3           | 1.8            |
| M3          | 17 17 59.9 | -37 26 09.13 | 1310           | +16.0           | 1.8            |
| M4          | 17 18 00.9 | -37 25 59.94 | 1020           | +15.2           | 1.6            |
| M5          | 17 18 01.4 | -37 26 23.90 | 277            | +16.9           | 1.4            |

### Table 2. Mopra and SEST observational parameters for G349.7+0.2.

| Parameter                        | Mopra | SEST |
|---------------------------------|-------|------|
| Observed frequencies (GHz)      | 110   | 86–270 |
| Total bandwidth (MHz)           | 64    | 2 \times 64 |
| No. of frequency channels       | 1024  | 2 \times 1000 |
| Velocity resolution (km s\(^{-1}\)) | 0.20  | 0.06–0.14 |
| Velocity coverage (km s\(^{-1}\)) | 160   | 60–100 |
| FWHHP beamwidth (arcsec)        | 43    | 57–20 |
| Area observed (arcmin\(^2\))    | 3.5 \times 4 | 1.5 \times 2 |
| Grid interval (arcsec)          | 30    | 24    |
| Integration time (min)          | 1     | 1     |

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Table 3. ATCA observational parameters for G349.7+0.2.

| Parameter                        | OH observations | H2CO | CH3OH |
|----------------------------------|-----------------|------|-------|
| Date                             | 1999 December   | 1998 | 2001  | 2002 April |
|                                  | 2000 June       | 1998 | May   | May       | April      |
| Central frequency (MHz)          | 1666            | 6030 | 6049  | 4829      | 6668       |
| Array configurations             | 1.5A, 6B        | 6D   | 6D    | 750A      | 1.5A       | 6A         |
| Primary beam (arcmin)            | ≈33             | ≈10  | ≈10   | ≈10       | ≈10        | ≈10        |
| Total bandwidth (MHz)            | 30              | 30   | 30    | 30        | 30         |
| Spectral line                    | 8               | 4    | 4     | 4         | 4          |
| Continuum                        | 128             | 128  | –     | –         | –          |
| No. of frequency channels        | 1024            | 1024 | 1024  | 2048      | 2048       | 2048       |
| Spectral-line cubes              | 1024            | 1024 | 1024  | 2048      | 2048       | 2048       |
| rms noise (mJy beam−1)           | 15 × 12         | 3 × 2| 2 × 2 | 37 × 10   | 4 × 2      | 2 × 1.5    |

2.2 Near-infrared observations

The NIR observations were carried out in 1999 June using the University of New South Wales Infrared Fabry–Perot narrow-band filter (UNSWIRF; Ryder et al. 1998), in conjunction with the Infrared Imager and Spectrometer (IRIS; Allen et al. 1993) on the 3.9-m Anglo-Australian Telescope (AAT). A pixel size of 0.77 arcsec resulted in a circular image of 100 arcsec in diameter. Observations were obtained in the 2.12 μm H2 1–0 S(1) transition, centred at RA (2000) = 17°17′58'', Dec. (2000) = −37°26′7'', and the 2.25 μm H2 2–1 S(1) transition, with a similar position. Each observation consisted of a set of five Fabry–Perot frames, equally spaced by 40 km s−1, centred on the average maser velocity. The velocity resolution was ≈75 km s−1. The integration time was 180 s per frame for all observations. The data were reduced using modified routines in the IRAF software package (Ryder et al. 1998). An off-line frame, with velocity offset by −400 km s−1 from the first on-source frame, was taken for subsequent continuum subtraction. The intensity was calibrated using additional observations of the standard star BS 6441. Final data cubes were fitted with the instrumental Lorentzian profile to determine the line flux for the H2 emission across the field. The resultant uncertainty in the line flux is less than 30 per cent. It should be noted that the images are not true velocity channel maps, because each pixel in a frame has a slightly different line centre velocity. Both the central wavelength and the spectral resolution vary between pixels (in a reproducible manner) by up to ≈20 km s−1. Calibration was achieved using an arc line, to give line centre maps.

To establish the spatial coordinates for the H2 images, we carried out observations with the Cryogenic Array Spectrometer Imager (CASPIR; McGregor et al. 1994) camera installed on the 2.3-m telescope at the Siding Spring Observatory in 1999 June. The observations were undertaken using standard filters: J (1.15–1.4 μm), H (1.55–1.8 μm) and K (2.0–2.4 μm). The selected pixel size of 0.5 arcsec yielded individual frames with a size of ≈2 arcmin. A total of nine frames, with 20-arcsec spatial overlap, was obtained with each filter. The exposure time was 180 s for an individual frame. For each filter, bias and dark frames were taken, as well as frames of the dome lamp light for flat-fielding. The data were reduced using modified routines in IRAF. No extended emission was detected and median sky frames were made by combining six neighbouring source frames. To make the final image, the nine observed frames per filter were combined in a mosaic covering a region of ≈5 × 5 arcmin2. For the astrometry, stars in the J-band mosaic were matched with Digital Sky Survey (DSS) stars. Stars which were also detectable in the K-band mosaic were then used as reference stars for astrometry of the UNSWIRF frames. The absolute positions have a maximum uncertainty better than 1 arcsec.

2.3 Molecular-line observations at cm wavelengths

We used the Australia Telescope Compact Array (ATCA), which consists of six 22-m antennas, to observe ground- and excited-state transitions of OH at 1.6, 4.7 and 6.0 GHz, the 4.8-GHz transition of H2CO and the 6.6-GHz transition of CH3OH. The observational parameters are listed in Table 3 and the observed molecular transitions in Table 4. For some observations the correlator configuration also allowed a wideband setting (128 MHz band over 32 channels) for observations of continuum emission, in addition to the narrow spectral-line mode (see Table 3). The calibration source PKS 1934–638 was observed at each frequency to provide primary flux density and bandpass calibration. An observing cycle was used in which target source integrations were bracketed by short observations of the phase calibrator PKS 1718–649 used for calculation of the complex antenna gains. For the OH ground-state transitions the

| Molecule | Frequency (MHz) | Transition |
|----------|----------------|------------|
| OH       | 1665           | 2Π3/2 J = 3/2 |
| OH       | 1667           | 2Π3/2 J = 3/2 |
| OH       | 4660           | 2Π1/2 J = 1/2 |
| OH       | 4751           | 2Π1/2 J = 1/2 |
| OH       | 4765           | 2Π1/2 J = 1/2 |
| OH       | 6031           | 2Π1/2 J = 5/2 |
| OH       | 6035           | 2Π3/2 J = 5/2 |
| H2CO     | 4829           | 111 − 110   |
| CH3OH    | 6668           | 51 − 60A+   |
observing band was centred at 1666 MHz to include emission from
both ‘main’ lines at 1665 and 1667 MHz. The OH excited-state ob-
servations consisted of two or three contiguous 10-min integrations
on-source with the observing band set at the different transition
frequencies for each integration. Line-free channels were used for
subtraction of the continuum emission from all channels to form
spectral-line data cubes and, in some cases, to provide continuum
images. The rms noise values for the final spectral-line cubes are
listed in Table 3.

A continuum image at 18 cm was produced from two data sets
at 1666 MHz formed by averaging about 350 of the 1024 channels,
which were line-free. The continuum image at 6 cm was constructed
by combining data at 6035 and 4829 MHz. For the 6035 MHz obser-
vations the 128 MHz wideband configuration was used. However,
for the 4829 MHz data, no H$_2$CO was detected and hence, the cen-
tral 1800 channels of the 4 MHz spectral band were able to be
used. Because of different pointing centres and central frequencies
for the two data sets, the images were produced using mosaicking
and multifrequency synthesis techniques from the MIRIAD software
package (Sault & Killeen 1997).

3 RESULTS AND ANALYSIS

3.1 SNR morphology

In Fig. 1, we show the continuum images of G349.7+0.2 at 18 and
6 cm. The 18-cm image has a full width at half-maximum (FWHM)
synthesized beam of 9.0 × 5.8 arcsec$^2$ [position angle (PA) = −1°]
and an rms noise of 1.5 mJy beam$^{-1}$ and is similar to existing radio
images of the region (Fraile et al. 1996; Brogan et al. 2000). The 6 cm
image has a synthesized beam of 2.5 × 1.8 arcsec$^2$ (PA = −5.7°) and an rms noise of 0.2 mJy beam$^{-1}$. Only the bright eastern
part of the SNR was detected at 6 cm. The emission to the west is
too weak to be detected at the higher frequency with the available
sensitivity and resolution. A consequence of the shortest baselines
of the ATCA configurations used for this work is that the 6-cm
observations are only sensitive to structures ≤2 arcmin in extent,
while at 18 cm structures larger in scale than 5–8 arcmin will be
resolved out. The integrated flux densities are 15.5 and 6.6 Jy at
2 arcmin in extent, and in some cases, to provide continuum
images. The rms noise values for the final spectral-line cubes are
listed in Table 3.

Fig. 6 shows contours of velocity-integrated (10–20 km s$^{-1}$) $^{12}$CO
1–0 emission obtained with the SEST overlaid on the 18 cm con-
tinuum image of the SNR. The molecular gas peaks at position
RA (2000) = $17^h17^m59.6^s$, Dec. (2000) = −37°26′32.0″, which is
close to the position of maser M1. Molecular maps of $^{12}$CO 2–1
emission, as well as $^{13}$CO, HCO$^+$ and HCN emission (not shown),
are remarkably similar to the $^{12}$CO 1–0 image in Fig. 6. Our results
are consistent with the $^{12}$CO maps of Dubner et al. (2004), also
obtained with SEST. For the CS, $^{12}$CO and SO observations, emis-
sion was strongest towards maser M1. No emission was detected
from the molecule SiO.

3.2 Millimetre-line emission

Several molecular clouds were detected along the line of sight to
G349.7+0.2. Fig. 3 shows a sample $^{12}$CO 1–0 spectrum towards the
SNR in the velocity range $−40$ to $+80$ km s$^{-1}$. There are features
seen at $−10$, $+6$ and $+16$ km s$^{-1}$. To identify the molecular cloud
associated with the SNR, we have assumed that the cloud has a ve-
cocity close to the maser velocity, that is $+16$ km s$^{-1}$. Fig. 4 shows
the molecular-line spectra for a variety of transitions and species
in the velocity range $−10$ to $+40$ km s$^{-1}$. All measured towards
the peak position of the molecular cloud described above, except for
the CS 3–2 and $^{12}$CO $2(3,1,1)$–$1(2,0)$ transitions, which were measured
towards the maser position M1. Since the $^{13}$CO spectra taken with
the Mopra telescope have different grid positions and intervals to
those from the SEST data, the $^{13}$CO 1–0 spectrum shown in Fig. 4 is
from the pointing at RA (2000) = $17^h17^m58.5^s$, Dec. (2000) =
−37°26′10.1″, which is the closest grid point to the SEST peak po-
osition. Most of the spectra appear to have symmetric, Gaussian-like
profiles. The line profile of HCN 1–0 shows all three hyperfine
components and was fitted with three Gaussian profiles. However,
some spectra do show asymmetric profiles and flattening, indica-
tive of self-absorption in the molecular cloud. The HCO$^+$ spectra,
shown in Fig. 5, demonstrate this well. The self-absorption is most
likely caused by cold gas in front of the warmer gas associated with
G349.7+0.2, as seen in other SNRs (e.g. van Dishoeck et al. 1993).

The line parameters derived from the fit to the spectral pro-
files are summarized in Table 5. The spectra have centre velocities
between 12.9 and 16.7 km s$^{-1}$, which is in good agreement with the
OH maser velocities in Table 1. The linewidths range from 2.7 to
6.5 km s$^{-1}$, with an average value of ≈4 km s$^{-1}$.

3.3 Properties of the molecular gas

To estimate the physical properties of the molecular gas we used
a statistical-equilibrium excitation code RADEx$^1$ supplied by J. H.
Black (private communication) to model the molecular line emis-
sion. The code uses a mean escape probability (MEP) approximation
for radiative transfer (for more details see Jansen, van Dishoeck &
Black 1999; van der Tak et al. 2007). For a given kinetic tempera-
ture and density of the gas, together with a total molecular column
density and species linewidth, the code calculates the molecular line
intensities, which can be compared with observed values.

$^{12}$CO lines are commonly used to derive the kinetic temperature
of the gas because they are easily thermalized ($T_{ex} = T_{kin}$), even at
low densities. The estimated $^{12}$CO 1–0/2–1 line ratio differs from
unity, which implies that self-absorption might be present and/or
that there are molecular clumps with different filling factors for the

$^1$ Now also available online at http://www.strw.leidenuni.nl/~moldata/
radex.html.
two sets of observations (the beam sizes range from 20 to 55 arcsec). Indeed, we have already established that our observations show some degree of self-absorption. In addition, H$_2$ emission is typically detected in highly clumped gas and our higher frequency data will also be subject to beam dilution effects. To be able to compare our line intensities for the same molecular species, a correction must be made for the assumed or derived source size. We adopt a source size of $40 \times 90$ arcsec$^2$ for the $^{12}$CO cloud, which is the size estimated from both the H$_2$ and OH emission (see below). This coincidence implies that the value could be the true size of the cloud interacting with the SNR. The actual source brightness temperature, corrected for the source size, can be found from $T_S = T_{mb}(1 + \theta_B^2/\theta_S^2)$, where $\theta_B$ and $\theta_S$ are the beam and source FWHM, respectively, and $T_{mb}$ is the observed main-beam brightness temperature (e.g. Rohlfs & Wilson 1996). We derive $T_{{^{12}\text{CO} 1-0}} \approx 28$ K and $T_{{^{12}\text{CO} 2-1}} \approx 36$ K, and a $^{12}$CO 2–1/1–0 line intensity ratio of $\approx 1.3$. Importing these values into the RADEX code and adopting an uncertainty of 10 per cent in $T_S$, we derive a kinetic temperature of...
Figure 2. Grey-scale image of the $^{12}$CO 1–0 emission obtained with the 12-m National Radio Astronomy Observatory (NRAO) antenna, integrated between $+14.5$ and $+20.5$ km s$^{-1}$ and convolved to a $60 \times 60$ arcsec$^2$ beam from Reynoso & Mangum (2001). The contours represent the 18 cm continuum emission from G349.7+0.2 with the levels same as in Fig. 1. Cloud 1 is coincident with the SNR G349.7+0.2, and cloud 2 is coincident with an UC H II region IRAS 17147–3725 located to the southeast of the SNR, represented by a single radio contour.

Figure 3. $^{12}$CO 1–0 spectrum (intensity scale is in antenna temperature ($T_A$) units) towards the SNR G349.7+0.2 in the range $-40$ to $+80$ km s$^{-1}$. Molecular clouds are present at $-10$, $+6$ and $+16$ km s$^{-1}$. The absorption around $-30$ km s$^{-1}$ indicates that spectra used for baseline subtraction had emission at that velocity.

$T_{\text{kin}} \approx 60 \pm 15$ for a gas density of $10^4$ cm$^{-3}$, or $T_{\text{kin}} \approx 45 \pm 5$ for a gas density of $10^5$–$10^6$ cm$^{-3}$. These values may be lower limits because of the presence of self-absorption. The measured line ratio of $^{12}$CO to $^{13}$CO 1–0 main-beam brightness temperature was $\approx 4.5$, which implies that the $^{12}$CO emission is optically thick. In this case, the derived kinetic temperature refers to the region from which the optically thick $^{12}$CO emission arises, which might not apply to the entire molecular cloud. Using an overall $^{12}$C to $^{13}$C ratio of $50 \pm 20$ (e.g. Langer & Penzias 1990), we estimate an upper limit for the $^{12}$CO 1–0 optical depth of $\approx 16$ and for $^{13}$CO 1–0 an optical depth of $\approx 0.3$.

To derive the density of the molecular cloud it is common to use molecular species with a dipole moment larger that of $^{12}$CO, such as CS. The distribution of the CS 2–1 emission (not shown here) implies that CS emission is concentrated in a much smaller region than for the $^{12}$CO emission, so a source size of $\approx 35$ arcsec is used to correct the CS brightness temperatures for beam dilution effects. Modelling the two CS transitions with kinetic temperatures of $\approx 45$ K implies a gas density of $n(H_2) \approx 1.6 \times 10^9$ cm$^{-3}$. We note that our analysis is sensitive to the line ratio of the transitions used, which in turn depends on the adopted source size.

The excitation analysis implies a $^{12}$CO column density of $\approx 4 \times 10^{17}$ cm$^{-2}$. Applying the isotope abundance ratio of $\approx 50$, given above, we obtain a $^{13}$CO column density of $\approx 8 \times 10^{15}$ cm$^{-2}$. The CS column density derived from the excitation analysis is $\approx 3 \times 10^{16}$ cm$^{-2}$. The non-detection of the CS 5–4 line is also consistent with these physical parameters for the gas. We assume that other molecular transitions have a small opacity. In fact, the ratios of the hyperfine lines in HCN, ($F = 0 - 1$)/($F = 2 - 1$) $\approx 1.3$ and ($F = 1 - 1$)/($F = 2 - 1$) $\approx 2.9$, deviate significantly from the LTE values of 0.2 and 0.6 (e.g. Chin et al. 1997), respectively, suggesting that HCN is optically thin. For an estimation of the total column density for the molecular cloud associated with the SNR we use the standard fractional abundance of $^{12}$CO relative to $H_2$ of $10^{-4}$ (e.g. Irvine, Goldsmith & Hjalmarson 1987; van Dishoeck et al. 1993), which implies $N(H_2) \approx 4 \times 10^{21}$ cm$^{-2}$. For the other molecules species observed we used the relation for optically thin transitions (e.g. Rohlfs & Wilson 1996):

$$N_i = 2.07 \times 10^3 \frac{g_i \nu^3}{h \epsilon_{\lambda} A_{\lambda}} \int T_{\text{SD}} d\nu,$$

where $g_i (i = u, l)$ is the number of states with the same energy ($g_i = 1 + 2l$), $A_{\lambda}$ is the Einstein A-coefficient of spontaneous emission, and $\nu$ is transition frequency in units of GHz. From this relation we derive the column densities for HCO$^+$ and HCN, using the same source size as for $^{13}$CO, and for SO using the source size for CS. The values are listed in Table 8.
3.4 H$_2$ emission

Fig. 7 shows the velocity-integrated 1–0 and 2–1 S(1) H$_2$ line emission detected towards G349.7+0.2. The 1σ noise in the 1–0 line is $6 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ and in the 2–1 line is $4 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The southeastern part of the 2.12 μm H$_2$ 1–0 S(1) emission is truncated by the instrumental field of view, but the total extent of the emission can be determined from the 2.25 μm H$_2$ 2–1 S(1) image. The H$_2$ emission extends about 1.5 arcmin with a maximum width of 40 arcsec. It has a clumpy structure containing several peaks (knots), which are about 15 arcsec in size. In general, the maser positions are located near these H$_2$ knots. The line fluxes of the knots are corrected for a minimum extinction of $A_K \approx 3$ mag because the source is located beyond the Galactic Centre. The values are summarized in Table 6 and the numbering of the knots is the same as for the masers. After correction for extinction, the intensity ratio of the 1–0 and 2–1 S(1) H$_2$ transitions is calculated to be about 5–6. However, we note that because of the uncertainties in the absolute calibration at the two line frequencies, the derived line ratios may have a (constant) scaling error of up to 50 per cent. There is a range of line centre velocities across the source, as indicated in Fig. 7. Most of the H$_2$ mission has a line centre velocity around $-40$ km s$^{-1}$. However, the emission from H$_2$ knots 1 and 3 has a peak line centre velocity of $+40$ km s$^{-1}$, while the emission from knot 2 has a peak velocity of $-20$ km s$^{-1}$. As mentioned previously, the velocity resolution is low ($\approx 75$ km s$^{-1}$) and we cannot determine the peak velocities very accurately ($\approx 20$ km s$^{-1}$ uncertainty). Nevertheless, we can report that H$_2$ emission was detected in the velocity range of $-40$ to $+40$ km s$^{-1}$, which encompasses both the velocities of the OH(1720 MHz) masers and the parent molecular cloud, at roughly $16$ km s$^{-1}$. The velocity-integrated H$_2$ emission contours are superimposed on the 18-cm radio continuum grey-scale image in Fig. 8. We note that there is also a clump of H$_2$ emission coincident with the radio continuum peak, which is clear in the 2–1 S(1) line image, but has been truncated by the edge of the field of view in the 1–0 S(1) line image.

3.5 Search for ground- and excited-state OH maser emission

We have detected weak emission from the OH main-line masers at 1665 and 1667 MHz towards two locations in the observed field. The positions and flux densities of the sources are summarized in Table 7 and the maser profiles are shown in Fig. 9. One of the main-line masers, denoted MM(1), is located in the direction of the SNR. Its position is closest (offset by 5 arcsec in RA and 1 arcsec in Dec.) to that of maser M3 and emission was detected only in the 1665-MHz transition. The second maser, MM(2), was detected in both main-line transitions and is centred on the UC H II region IRAS 17147–3725. Therefore, MM(2) is clearly related to star formation. The peak velocity of the 1665-MHz transition of H$_2$ is somewhat different from the peak velocity of the 1667-MHz transition of $10$ km s$^{-1}$, but both velocities fall within the range for the molecular gas found towards the H II region ($10$–20 km s$^{-1}$). This discrepancy in the peak velocities of the masers may occur in star-forming regions (e.g. Masheder et al. 1994; Caswell 1999), indicating a slight difference in their formation sites in the molecular
The observed HCO+ 1–0 line profiles of the +16 km s⁻¹ molecular cloud towards G349.7+0.2. The line profiles show asymmetry and flattened profiles, suggestive of self-absorption. Intensity scale is in main-beam temperature $T_{mb}$.

Figure 5. The observed HCO+ 1–0 line profiles of the +16 km s⁻¹ molecular cloud towards G349.7+0.2. The line profiles show asymmetry and flattened profiles, suggestive of self-absorption. Intensity scale is in main-beam temperature $T_{mb}$.

could and consequent variations in the conditions producing the masers.

To date, main-maser lines have not been found detected coincident with OH(1720 MHz) masers in SNRs. There is an unresolved IRAS source IRAS 17146–3723 located ≈15 arcsec away from MM(1), but the angular resolution for the IRAS observations ranges from 0.5 to 2 arcmin between 12 and 100 μm. Both Reynoso & Mangum (2001) and Dubner et al. (2000) considered whether this source is dust heated by the SNR shock or a protostellar object. To investigate the nature of MM(1) towards G349.7+0.2, we examined the available IR data from the Two Micron All Sky Survey (2MASS) Point Source Catalogue (Skrutskie et al. 2006) and the Spitzer Space Telescope GLIMPSE Catalogue (Ramírez et al. 2008). There is a GLIMPSE source SSTGLMC G349.7294+00.1747 detected at 5.8 μm (8 mag) and 8.0 μm (6.5 mag), located 0.8 arcsec from MM(1), but with no 2MASS counterpart. For comparison, there is a GLIMPSE source SSTGLMA G349.7213+00.1208 located 0.7 arcsec from MM(2) with 6.5 mag at 5.8 μm and 4.8 mag at 8.0 μm, which does have a 2MASS counterpart. Thus, it would appear that MM(1) may also be related to star formation. However, detection of a possible HII region associated with MM(1) and the GLIMPSE source would be very difficult because the radio
Table 5. The first three columns list the observed molecular transitions and their frequencies ($\nu$) towards the SEST peak position, except for the CS and H$_2$CO transitions which are obtained towards M1. The fourth column lists the SEST and Mopra FWHM beam size, the fifth gives the observed main-beam brightness temperature ($T_{mb}$) and rms noise (upper limits are 2$\sigma$ values), while the last two columns list line velocities ($v_{LSR}$) and FWHM linewidths ($\Delta v_{LSR}$).

| Molecule | Transition | $\nu$ (GHz) | Beam size (arcsec) | $T_{mb}$ (K) | $v_{LSR}$ (km s$^{-1}$) | $\Delta v_{LSR}$ (km s$^{-1}$) |
|----------|------------|--------------|--------------------|--------------|-------------------------|-----------------------------|
| $^{13}$CO$^a$ | 1–0 | 110.197 | 43 | $3.9 \pm 0.2$ | 16.4 | 2.7 |
| $^{12}$CO | 2–1 | 230.538 | 23 | $31.1 \pm 0.1$ | 15.1 | 3.9 |
| CS | 1–0 | 115.271 | 45 | $17.8 \pm 0.2$ | 16.5 | 3.9 |
| | 5–4 | 244.935 | 21 | $0.7 \pm 0.1$ | 16.1 | 4.2 |
| | 3–2 | 146.969 | 34 | $0.5 \pm 0.1$ | 16.7 | 3.3 |
| | 2–1 | 97.981 | 52 | $<0.4$ | – | – |
| HCO$^+$ | 3–2 | 267.557 | 20 | $<0.3$ | – | – |
| | 1–0 | 89.188 | 54 | $2.1 \pm 0.1$ | 13.3 | 4.5 |
| HCN | 3–2 | 265.886 | 20 | $0.7 \pm 0.1$ | 16.1 | 3.9 |
| | 1–0 | 88.632 | 55 | $1.0 \pm 0.1$ | 12.9 | 3.3 |
| H$_2$CO | $2_{(1,2)}-1_{(1,1)}$ | 225.698 | 23 | $<0.2$ | – | – |
| | $3_{(0,3)}-2_{(0,2)}$ | 218.222 | 24 | $<0.2$ | – | – |
| | $2_{(1,1)}-1_{(1,0)}$ | 150.498 | 36 | $0.3 \pm 0.1$ | 16.8 | 6.5 |
| | $2_{(1,2)}-1_{(1,1)}$ | 140.839 | 38 | $<0.2$ | – | – |
| SO | $2_3-1_2$ | 109.252 | 47 | $<0.2$ | – | – |
| | $3_2-2_1$ | 99.299 | 50 | $0.5 \pm 0.1$ | 14.7 | 3.0 |
| SiO | 5–4 $v = 0$ | 217.105 | 24 | $<0.4$ | – | – |
| | 3–2 $v = 0$ | 130.268 | 40 | $<0.3$ | – | – |
| | 2–1 $v = 0$ | 86.846 | 57 | $<0.2$ | – | – |

$^a$From Mopra observations; $^b$values for the main hyperfine component.

Figure 6. Contours of the velocity-integrated (10–20 km s$^{-1}$) $^{12}$CO 1–0 emission obtained with the SEST with 45 arcsec resolution, overlaid on the 18 cm grey-scale radio continuum obtained with the ATCA. The contour levels are 16, 24, 32, 48, 63, 71 and 78 K km s$^{-1}$. The dots mark the grid positions of the SEST observations. The crosses mark the OH (1720 MHz) maser positions.

continuum emission from the SNR is very bright. As evidence, the nearby UC HII region IRAS 17147–3725 has a brightness comparable with the weakest emission measured from the SNR. Our search for the excited-state maser lines was unsuccessful and the limits given by the 1$\sigma$ rms values are listed in Table 3. The relationship between ground- and excited-state transitions of OH masers has been studied in detail in star-forming regions observationally and theoretically (see e.g. Gray, Field & Doel 1992; MacLeod 1997; Pavlakis & Kylafis 1996, 2000, and references therein), and recently in molecular gas associated with SNRs.
Figure 7. Contours of the velocity-integrated $2.12 \, \mu m$ 1–0 S(1) line emission (left-hand panel) and $2.25 \, \mu m$ H$_2$ 2–1 S(1) line emission (right-hand panel). Note that flux densities are not corrected for extinction (which is assumed to be a minimum 3 mag in the $K$ ($2.12 \, \mu m$) band). The contours are for 1–0 S(1) emission: 3.3, 6.7, 13.2, 19.7 and $26.3 \times 10^{-5}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$; for 2–1 S(1) emission: 2.7, 3.6, 4.5, 5.3 and $6.2 \times 10^{-5}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The $1\sigma$ noise in the 1–0 line is $6 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ and in the 2–1 line is $4 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The crosses mark the OH (1720 MHz) maser positions. Line-centre velocities of H$_2$ emission are also indicated in the left-hand panel.

Table 6. Summary of results from UNSWIRF observations. The knots denote H$_2$ peaks near the five OH (1720 MHz) masers. All sets of features are numbered correspondingly. The second and third columns list the peak flux density of 1–0 and 2–1 S(1) H$_2$ lines, corrected for extinction as follows: $A_{2.12} = 3$ mag, $A_{2.25} = 2.7$ mag. The fourth and fifth columns list the total flux density of corresponding H$_2$ lines, corrected for extinction. The sixth and seventh columns list the luminosity of the corresponding H$_2$ lines for a source distance of 18 kpc. The eighth column gives the line ratio $R = L(1–0)/L(2–1)$. The absolute flux density measurements have less than 30 per cent uncertainty.

| Designation | $F_{\text{peak}}(1–0)$ ($\times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$) | $F_{\text{int}}(1–0)$ ($\times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) | $F_{\text{int}}(2–1)$ ($\times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) | $L(1–0)$ ($L_{\odot}$) | $L(2–1)$ ($L_{\odot}$) | $R$ |
|-------------|-------------------------------|-----------------|-----------------|----------------|----------------|---|
| Knot 1      | 24                            | 6.0             | 38              | 8.4            | 38             | 8  |
| Knot 2      | 52                            | 9.6             | 66              | 12             | 66             | 12 |
| Knot 3      | 43                            | 8.4             | 49              | 10             | 49             | 10 |
| Knot 4      | 36                            | 7.2             | 40              | 4.8            | 40             | 5  |
| Knot 5      | 44                            | 8.4             | 41              | 7.2            | 41             | 7  |
| total       | 52                            | 9.6             | 540             | 90             | 540            | 88 |

(Wardle 2007; Pihlström et al. 2008; McDonnell, Wardle & Vaughan 2008). Gray et al. (1992) proposed a correlation between masing at 1720 and 4765 MHz in warm gas ($T_{\text{kin}} > 100$ K), and between 1720 and 6035 MHz in cooler molecular gas, which was confirmed using single dish observations of star-forming regions (MacLeod 1997). Models by Pavlakis & Kylafis (1996, 2000) imply that OH transitions around 4.7 GHz are only excited in gas with higher density ($> 10^6$ cm$^{-3}$) than is required to produce the 1720-MHz maser. Furthermore, the transitions at 6031 and 6035 MHz require a strong far-infrared (FIR) radiation field. A satellite-line maser at 6049 MHz is more likely to be found, as it requires physical conditions not dissimilar to those needed for production of the 1720 MHz line, but it is expected to be very weak at densities $< 10^6$ cm$^{-3}$ (Pavlakis & Kylafis 2000), and would probably lie below our detection limits. Our results are therefore consistent with the OH excitation models.

3.6 Search for CH$_3$OH maser emission

Methanol (CH$_3$OH) masers are related to star formation and are often found to coexist with OH masers (e.g. Plambeck & Menten 1990; Phillips et al. 1998). We searched for CH$_3$OH maser emission at 6.6 GHz towards the location of the two OH main-line masers in the field of G349.7+0.2. Of particular interest was whether the MM(1) maser had a CH$_3$OH maser counterpart, in order to clarify its origin. However, no maser emission was detected; the $1\sigma$ rms limits are listed in Table 3. The conclusion is that either CH$_3$OH is not sufficiently abundant or that the local conditions (gas temperature, density and dust temperature) are such that only OH masers are favoured (Cragg, Sobolev & Godfrey 2002).

3.7 OH absorption

The 1665 and 1667 MHz OH absorption profiles towards G349.7+0.2 are shown in Fig. 10 in the velocity range $-150$ to $+70$ km s$^{-1}$. Hanning smoothed over three channels. Prominent features are present around $-110$, $-95$, $-65$, $-25$, $-10$, $+6$ and $+16$ km s$^{-1}$. The 1665-MHz profile differs from the 1667-MHz spectrum in having an additional feature at $\sim 70$ km s$^{-1}$. This feature originates from a bright maser located northwest of the SNR, outside the observed field of view. These OH absorption features are also seen in H$_2$ absorption (Caswell et al. 1975), and some of them (for which we have velocity coverage) are seen in our SEST $^{13}$CO spectra, that is features at $-10$, $+6$ and $+16$ km s$^{-1}$. The $+16$ km s$^{-1}$ feature, which we associate with the SNR because of the common velocity with the OH (1720 MHz) masers, is partially blended with the $+6$ km s$^{-1}$ feature. To investigate the distribution...
of the 16 km s\(^{-1}\) OH cloud we produced velocity-integrated (10–20 km s\(^{-1}\)) images of OH absorption with a resolution of 15 × 12 arcsec\(^2\) (PA = −3:2), degraded from the best available resolution to improve the image sensitivity. The OH images are shown in Fig. 11, overlaid on the 18-cm radio continuum image. The distribution of the OH cloud does not mirror the continuum emission, which would occur for a uniform overlaying absorption cloud, but appears as an elongated feature, 40 arcmin wide and 1.5 arcmin long, covering the region of the OH(1720 MHz) maser emission. We note that for the section of the SNR containing the masers the continuum emission is reasonably constant, which suggests that the variation in OH absorption is indicative of variations in OH column density. The two troughs in the OH absorption distribution coincide with the M2 and M4 maser locations. The 1665-MHz distribution is more extended than that of 1667 MHz, and there is an indentation in the OH absorption distribution near the compact MM(1) maser, shown in Fig. 11.

The optical depth \(\tau = -\ln[(T_L/T_C) + 1]\) was calculated from the spectral-line channel maps, where \(T_L\) and \(T_C\) are the intensities of the spectral line and continuum maps, respectively. The calculation was limited to regions with a continuum intensity greater than 25 mJy beam\(^{-1}\) because of the poor signal-to-noise ratio figure at weaker continuum levels. In Fig. 12, we compare the optical depth profiles and the line-to-continuum ratios towards the peak of the OH cloud. The optical depths are quite high, around 1.2–1.3. The relative intensity of the OH absorption in the 1667 and 1665 MHz lines is expected to have a ratio around 9/5 for an optically thin gas in local thermal equilibrium (LTE). The line ratio \(T_{1667}/T_{1665}\) in G349.7+0.2 is ~1.1, which is significantly different from the LTE ratio (~1.8), probably reflecting the high calculated optical depths. OH absorption is typically observed with low optical depths in the Galaxy, but higher values have been found towards some SNRs (e.g. Yusef-Zadeh, Wardle & Roberts 2003).

The OH column density for the LTE case can be obtained from (e.g. Crutcher 1977)

\[
N(1665 \text{ MHz}) = 4.2 \times 10^{14} T_{\text{ex}} \int \tau \, dv \, \text{cm}^{-2}.
\]

(2)

\[
N(1667 \text{ MHz}) = 2.3 \times 10^{14} T_{\text{ex}} \int \tau \, dv \, \text{cm}^{-2}.
\]

(3)

Modelling of the OH population levels implies that for \(T_{\text{kin}} \geq 20\) K an OH excitation temperature of 10 K is plausible (Yusef-Zadeh et al. 2003). Using the above values of the optical depth, we derive a peak OH column density of (2.8–4.7) \times 10^{15} cm\(^{-2}\). These values are consistent with the models for OH(1720 MHz) excitation (Elitzur 1976; Lockett et al. 1999) and with the model for OH production in C-type shocks (Wardle 1999). Modelling the OH excitation using all four ground-state OH transitions, Hewitt, Yusef-Zadeh & Wardle (2008) found that the line profiles from their observations of 15 SNRs with the Green Bank Telescope are consistent with molecular gas with temperatures of 30–100 K, OH column densities of 10^{15}–10^{17} cm\(^{-2}\) and gas densities of ~10^3 cm\(^{-3}\). Hewitt et al. (2008) detected enhanced 1720-MHz emission in G349.7+0.2, but were not able to resolve any corresponding main-line absorption lines.

### Table 7. Parameters of the main-line OH masers at 1665 and 1667 MHz detected towards the region of G349.7+0.2.

| Parameter | MM(1) | MM(2) |
|-----------|-------|-------|
| RA (2000) (h m s) | 17 17 59.3 | 17 18 11.1 |
| Dec. (2000) (° ′ ′ ′) | −37 26 10.00 | −37 28 23.93 |
| 1665 peak (Jy) | 0.09 | 0.06 |
| 1665 V\(_{\text{peak}}\) (km s\(^{-1}\)) | 21 | 16 |
| 1667 peak (Jy) | − | 0.10 |
| 1667 V\(_{\text{peak}}\) (km s\(^{-1}\)) | − | 10 |

Figure 8. Contours of 2.12 \(\mu\)m H\(_2\) 1–0 S(1) emission overlaid on the 18-cm grey-scale radio continuum image of G349.7+0.2. The contour levels (not corrected for extinction) are 3.2, 9.6, 16 and 26 \(\times 10^{-5}\) erg s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\). The crosses mark the OH(1720 MHz) maser positions, which are again shown numbered.
Figure 9. Main-line maser profiles towards two locations in G349.7+0.2. MM(1) is located within the SNR contours, and MM(2) originates from the UC H\textsc{ii} region located southeast from the remnant.

3.8 H$_2$CO absorption

H$_2$CO absorption at 4829 MHz is readily found in H\textsc{ii} molecular cloud complexes, where H\textsc{ii} regions are embedded in dense molecular clouds. There have been only a few such absorption detections towards SNRs (e.g. Whiteoak & Gardner 1974; Slysh et al. 1980; DeNoyer 1983; Reynoso & Goss 2002), where the associated continuum emission and resultant absorption is usually much fainter than for surveyed H\textsc{ii} regions. We did not detect H$_2$CO absorption towards G349.7+0.2, but there was weak absorption towards the nearby UC H\textsc{ii} region, with an optical depth of $\approx$1 and a column density of $\approx$$4.3 \times 10^{15}$ cm$^{-2}$ (for an adopted excitation temperature of 10 K and a linewidth of 5 km s$^{-1}$). For a 3$\sigma$ upper limit and a linewidth of 5 km s$^{-1}$, we estimate an optical depth $<$0.013 and an H$_2$CO column density $<$1.7 $\times$ 10$^{13}$ cm$^{-2}$ in the direction of the SNR.

4 DISCUSSION

4.1 Kinematics and chemistry of molecular gas

The parameters derived from the millimetre-line observations of various molecular species for the molecular cloud associated with G349.7+0.2 of $n$(H$_2$) $\approx$ 10$^5$ cm$^{-3}$ and $T_{\text{kin}}$ $>$ 45 K, are consistent with values required for the production of OH(1720 MHz) masers by shock excitation (Lockett et al. 1999). However, the measured millimetre linewidths of $\approx$4 km s$^{-1}$ for all the molecular transitions we observed, are smaller than those expected from shocked gas ($\geq$10 km s$^{-1}$). Although the shock front containing the OH(1720 MHz) masers will be seen mostly perpendicular to the line.
of sight (hence showing minimal line broadening), some broadening is expected due to deflection of the shock in clumpy pre-shock gas (Turner & Lubowich 1991). High-velocity wings were not detected in the lines from the low $^{12}$CO transitions, but they may be too weak to be seen with the short integration times used here. Dubner et al. (2004) reported asymmetry in the $^{12}$CO line profiles towards the cloud borders, indicating the line broadening and kinematic signatures of shocked gas. We find that the peak velocities vary across the source for all the species observed, but there was no particular trend. It is probable that the shifts are caused by self-absorption in the spectral lines due to the presence of cold, pre-shocked gas, as found in other SNRs (e.g. van Dishoeck et al. 1993). Our beam resolution is such that beam dilution is expected to render any SO enhancement undetectable, unless the species was distributed over a substantial distance. The derived SO abundance of $\approx 3 \times 10^{-8}$ is an order of magnitude greater than in TMC-1, but is consistent with the value found in L134N. More spatially sensitive observations are needed to determine whether SO is enhanced in G349.7+0.2.

Another molecule predicted to be enhanced in shocks is SO. This enhancement depends on the H$_2$/O ratio, the C/O ratio, and on the initial form (atomic or molecular) of sulphur (see van Dishoeck et al. 1993, and references therein). Pineau Des Forêts et al. (1993) suggested that SO can be found at distances up to $10^{15}$ cm from the shock front. The telescope resolution at the SO frequency observed is such that beam dilution is expected to render any SO enhancement undetectable, unless the species was distributed over a substantial distance. The derived SO abundance of $\approx 3 \times 10^{-8}$ is an order of magnitude greater than in TMC-1, but is consistent with the value found in L134N. More spatially sensitive observations are needed to determine whether SO is enhanced in G349.7+0.2.

Early observations reported an enhancement of HCO$^+$ towards IC 443 (Dickinson et al. 1980; De Noyer & Frerking 1981), which was contrary to predictions for slow shocks (Iglesias & Silk 1978), but could be explained by the increased ionization expected in SNRs (Elitzur 1983). However, subsequent observations found that the HCO$^+$ abundance in IC 443 was not enhanced by the SNR shock (Ziurys et al. 1989) and even decreased in the high density gas, probably due to more rapid dissociative recombination with electrons and reactions with H$_2$O (van Dishoeck et al. 1993). Our beam-averaged result of $7.5 \times 10^{-8}$ implies that the HCO$^+$ abundance
Figure 12. Line profiles of the 1665 and 1667 MHz OH optical depth (upper panels), and profiles of the line-to-continuum ratio (lower panels) towards the peak of the OH cloud. The spectra have been Hanning smoothed over three channels. The arrow indicates the velocity of the material associated with the remnant.

Table 8. Molecular column densities, \( N(\text{mol}) \), and abundances, \( X = \frac{N(\text{mol})}{N(H_2)} \) for \( N(H_2) = 4 \times 10^{21} \text{ cm}^{-2} \), of the molecular cloud interacting with the SNR G349.7+0.2. For comparison, abundances of the shocked molecular gas in SNR IC 443 (van Dishoeck et al. 1993) are listed, as well as those of the dark clouds TMC-1 and L134N (Ohishi et al. 1992). Note that abundance values are always assumed for \(^{12}\text{CO} \) and \(^{13}\text{CO} \).

| Molecule | G349.7+0.2 | IC 443\( ^a \) | TMC-1 | L134N |
|----------|------------|---------------|--------|-------|
| \(^{12}\text{CO} \) | 4 \times 10^{17} | 1 \times 10^{-4} | 10^{-4} | 8 \times 10^{-5} | 8 \times 10^{-5} |
| \(^{13}\text{CO} \) | 8 \times 10^{15} | 2 \times 10^{-6} | 2 \times 10^{-6} | 2 \times 10^{-6} | - | - |
| HCO\(^+\) | 3 \times 10^{14} | 7.5 \times 10^{-8} | 1 \times 10^{-9} | 3 \times 10^{-10} | 8 \times 10^{-9} | 8 \times 10^{-9} |
| HCN | 1.3 \times 10^{14} | 3.2 \times 10^{-8} | 3 \times 10^{-8} | 9 \times 10^{-9} | 2 \times 10^{-8} | 4 \times 10^{-9} |
| CS | 3 \times 10^{13} | 7.5 \times 10^{-9} | 6 \times 10^{-9} | 8 \times 10^{-9} | 10^{-9} | 10^{-9} |
| SO | 1.2 \times 10^{14} | 3.0 \times 10^{-8} | 8 \times 10^{-9} | 5 \times 10^{-9} | 2 \times 10^{-9} | 2 \times 10^{-9} |
| H\(^2\)CO | <5 \times 10^{13} | <1.2 \times 10^{-8} | 7 \times 10^{-9} | 2 \times 10^{-8} | 2 \times 10^{-8} | 2 \times 10^{-8} |
| SiO | <3 \times 10^{13} | <7.5 \times 10^{-9} | <2 \times 10^{-9} | <2 \times 10^{-12} | <2 \times 10^{-12} | <2 \times 10^{-12} |

\( ^a \)It is suggested that the shocked gas in IC 443 has two components: \( X_1 \) abundances correspond to shocked gas with \( n(H_2) \sim 10^5 \text{ cm}^{-3} \) and \( T_{\text{kin}} \sim 80 \text{ K} \), while \( X_2 \) abundances correspond to shocked gas with \( n(H_2) \sim 3 \times 10^6 \text{ cm}^{-3} \) and \( T_{\text{kin}} \sim 200 \text{ K} \) (see van Dishoeck et al. 1993, for more details).

\( ^b \)Derived for a single component model.

is either enhanced in G349.7+0.2, or that that the source size used for the beam correction of the HCO\(^+\) data was incorrect. As for SO, more spatially sensitive observations are needed to determine if there is an enhanced abundance of HCO\(^+\) in G349.7+0.2.

4.2 Shocked H\(_2\)

The measured H\(_2\) 1–0/2–1 line ratio of 5–6 is somewhat lower than the ratio of 10–20 expected for C-shocks (Burton et al. 1988). A lower line ratio can be produced in J-shocks, where the vibrational ground-states of H\(_2\) are generated by a cascade following collisional excitation of excited electronic states. However, this type of shock cannot account for the high 1–0 S(1) line intensities observed in G349.7+0.2 (Hollenbach & McKee 1989). A very low line ratio (\( \approx 2 \)) can be measured for fluorescent H\(_2\) emission produced by radiative excitation of low density gas by UV photons (Black & Dalgarno 1976). UV excitation can also produce higher line ratios in molecular gas of density \( 10^5–10^6 \text{ cm}^{-3} \) (Burton, Hollenbach &
Although, however, to generate 1–0 S(1) emission with a peak of 0.005 erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$, as found in G349.7+0.2, the far-UV (FUV) radiation field needs to be $>10^4$ G$_0$, where G$_0$ represents the FUV radiation field equivalent to 1.6 $\times$ 10$^{-3}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (Burton et al. 1990). This is an unusually high value to be produced by only a few young stars. For example, early-type B stars typically produce a field of $\approx$10$^3$ G$_0$ (note that strictly this is a function of the distance from the star). Burton et al. (1990) showed that less than 10$^{-3}$ of the energy of 6–13.6 eV photons is re-emitted in the 1–0 S(1) line. The total NIR H$_2$ 1–0 S(1) line luminosity of G349.7+0.2 is about 500 L$_{\odot}$ (Table 6), so an exciting source would need to emit 5 $\times$ 10$^3$ L$_{\odot}$ in 6–13.6 eV photons, with an even higher bolometric luminosity. Therefore, the H$_2$ emission we detect is too bright and widespread to be produced by UV excitation from a star and, despite the lower than expected line ratio, must be produced by the SNR shock. One possible explanation is a combination of gas components with different physical properties contributing to the detected H$_2$ emission. From observations of excited H$_2$ S(0)–S(7) lines with the Spitzer Space Telescope IRS spectrograph in 5–15 and 12–42.2 $\mu$m bands, Hewitt et al. (2009) found that two components are required to produce the observed H$_2$ line intensity: a slow (~10 km s$^{-1}$) C-type shock propagating into dense gas [n(H$_2$) $\sim$ 10$^3$ cm$^{-3}$, T $\sim$ 500 K, N(H$_2$) $\sim$ 2.8 $\times$ 10$^{23}$ cm$^{-2}$] and a faster (~40 km s$^{-1}$) C-type shock propagating into lower density gas [n(H$_2$) $\sim$ 10$^4$ cm$^{-3}$, T $\sim$ 1600 K, N(H$_2$) $\sim$ 5.2 $\times$ 10$^{18}$ cm$^{-2}$]. They also detected ionic lines (mainly [Fe ii]), which could be explained with models of a J-shock travelling in hot, low density gas [n(H$_2$) $\sim$ 700 cm$^{-3}$, T $\sim$ 7000 K]. Multiple gas components are often found in molecular clouds interacting with SNRs (e.g. van Dishoeck et al. 1993; Reach et al. 2005; Hewitt et al. 2006). J-shocks will dissociate H$_2$ and then ionize the atomic hydrogen, eventually producing the H$^+_2$–1 emission, while C-shocks will provide the H$_2$–2–1 emission. Hence, a mix of shocks along the line of sight might produce both an elevated 1–0 emission for C-shocks and too high a 2–1 emission for the J-shock, resulting in the line ratio we observed.

In shocked gas the 1–0 S(1) line contributes typically 5–10 percent of the total H$_2$ luminosity (e.g. see Burton 1992). The H$_2$ luminosity of the source would therefore be high, $\approx$5 $\times$ 10$^3$ L$_{\odot}$ at the SNR distance of 18 kpc. This is approximately five times higher than the $\approx$10$^3$ L$_{\odot}$ emitted in H$_2$ lines by IC 443 (Burton et al. 1988). It is also brighter than the extended fluorescent H$_2$ line emission associated with several massive star-forming complexes (e.g. 300 L$_{\odot}$ from the PDR emission around the Orion Molecular Cloud-One; Burton & Puxley 1990).

There is morphological evidence that the H$_2$ emission is related to the SNR shock in G349.7+0.2. Fig. 8 shows that the H$_2$ filaments coincide with the western edge of the bright continuum shell. The H$_2$ knots are associated with the locations of OH (1720 MHz) masers, which are produced by collisional excitation. This morphological coincidence between the H$_2$ and radio continuum emission, and between the H$_2$ and maser emission suggests that these phenomena are shock-related. Furthermore, our H$_2$ emission is strikingly similar to emission detected by the Spitzer Space Telescope IRAC camera in the 5.8 band (Reach et al. 2006), which has a shocked origin, as confirmed by the IRS observations of Hewitt et al. (2009).

Dubner et al. (2004) have also mapped G349.7+0.2 in the $^{12}$CO 1–0, 2–1 and 3–2 transitions, with a somewhat different survey area. While their integrated $^{12}$CO 1–0 and 2–1 maps are similar to our corresponding maps, their 3–2 map is distinct and matches the morphology of the H$_2$ emission well. The authors noted this difference and that their linewidths and derived gas density do not imply shocked molecular gas. However, the higher than unity line ratio between the three $^{12}$CO transitions (1–0, 2–1 and 3–2) at the peak of the cloud plus a possible asymmetry in the $^{13}$CO 2–1 and 3–2 line profiles (which we ascribe to self-absorption) are indicative of shocked gas. Dubner et al. (2004) suggest that the SNR is in front of the molecular cloud which it is impacting, with the eastern side being pushed away from us, and the western side of the SNR being pushed towards us.

The H$_2$ emission we detect shows a wide range of velocities from $-$40 to $+$40 km s$^{-1}$. However, there are no molecular cloud components at $-$40 or $+$40 km s$^{-1}$ observed in our $^{12}$CO or OH data. This is consistent with similar observations obtained towards other SNRs associated with OH (1720 MHz) masers G359.1–0.5 and G357.7–0.1 (Lazendic et al. 2002, 2004). It is likely that our arcsecond-scale NIR observations have the sensitivity to detect individually accelerated molecular clumps, while the mm and cm molecular data are sensitive to the bulk motion of the molecular gas, with ambient velocities. The H$_2$ observations reveal the shocked gas viewed from different angles, while the mm observations mostly probe the molecular gas along the line of sight and the optically thicker and colder outside layers of the molecular cloud. In the case of the SNR 3C 391, which is also associated with OH (1720 MHz) maser emission, Reach & Rho (1999) detected broad molecular lines (~20 km s$^{-1}$) only from a small gas clump (labelled 3C 391:BML) less than 0.6 pc in size. Such a feature would be about 6 arcsec in size if located at the distance of G349.7+0.2. Comparing the distribution of NIR H$_2$ emission and $^{12}$CO emission for 3C 391, Reach et al. (2002) further showed that broad-line $^{12}$CO emission does follow shocked H$_2$ emission, but that the line strength of the broad-line component was 10 times weaker than for the 3C 391:BML clump, which coincides with the OH (1720 MHz) maser. In summary, there are several factors which could explain the non-detection of broad molecular lines in an SNR suspected of interaction with a molecular cloud: the lack of high spatial resolution in the observations, confusion with ambient gas (i.e. self-absorption) and with higher $^{12}$CO transitions (Reach & Rho 1999).

4.3 Shocked OH and maser emission

Fig. 13 shows contours of velocity-integrated OH absorption at 1667 MHz overlaid on the contours of velocity-integrated H$_2$ emission. Good correlation between the OH and H$_2$ distributions is a strong indication that the OH gas is generated in the shocked regions. Other evidence to support the shock origin of the OH gas comes from the association of the OH peaks with the masers. The OH column density derived in Section 3.7 yields an OH fractional abundance of (0.4–1.0) $\times$ 10$^{-6}$, indicating that the OH abundance in G349.7+0.2 might be three times higher than in dark clouds (e.g. $\sim$3 $\times$ 10$^{-7}$; Ohishi et al. 1992). An enhanced OH abundance towards an SNR (IC 443) was first reported by DeNoyer (1979), but shock models do not predict such an enhancement (Draine, Roberge & Dalgarno 1983; Hollenbach & McKee 1989; Kaufman & Neufeld 1996). For temperatures above 400 K, any OH formed will be rapidly converted into H$_2$O through reactions with H$_2$. However, X-rays from the interior of the remnant can penetrate the surrounding molecular cloud and eject photo-electrons, which then collisionally excite the Werner Lyre band of H$_2$, providing enough energy to dissociate the H$_2$O molecules into OH, but not enough to dissociate the OH (Wardle 1999). The process of forming abundant OH occurs when the temperature drops to a point where the conversion of OH back...
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Figure 13. Contours of OH(1667 MHz) absorption distribution between 10 and 20 km s$^{-1}$ (light lines) superimposed on that of 2.12 µm H$_2$ 1–0 S(1) emission (heavy lines) which have been convolved to a similar resolution. The two distributions show a good correlation. The OH contour levels are the same as in Fig. 11, and the H$_2$ contour levels are 3.4, 10, 17 and $27 \times 10^{-4}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The crosses mark the OH(1720 MHz) maser positions.

into H$_2$O ceases. A warm, dense layer rich in OH develops at the rear of the shock, ideal for the collisional pumping of OH(1720 MHz) masers. The upper value of the derived OH abundance in G349.7+0.2 is consistent with predictions for the dissociation of 1 per cent of the water by the SNR X-ray flux (Wardle 1999).

Our non-detection of excited-state OH masers is consistent with previous searches: Fish, Sjouwerman & Pihlström (2007) searched for 6-GHz OH masers towards 10 SNRs with the Effelsberg 100-m telescope; Pihlström et al. (2008) searched for 4.7-, 7.8-, 8.2- and 23.8-GHz OH transitions in four SNRs with the Very Large Telescope; and McDonnell et al. (2008) searched for the 6-GHz OH transitions with the Parkes 64-m telescope in about 40 SNRs, including sources from the Magellanic clouds and G349.7+0.2. These results suggest that the shock conditions suitable for the production of 1720-MHz OH transitions do not support the other OH transitions, even those at 6049 and 4765 MHz, which have the most compatible requirements. Interestingly, Wardle (2007) found that for OH column densities larger than $10^{17}$ cm$^{-2}$, the 6049 MHz masers switch on while the 1720-MHz transition is quenched, even with suitable gas densities and temperatures for the production of 1720-MHz masers, suggesting that the higher frequency line might serve as a complementary signpost of warm, shocked gas. Unfortunately, a dedicated search for the 6049-MHz OH line by McDonnell et al. (2008) was unsuccessful. However, they found indications that this transition is more sensitive than the 1720 MHz line to velocity coherence. Similarly, searches for the 22-GHz H$_2$O maser transition in about 20 SNRs reported no detections (Claussen et al. 1999; Woodall & Gray 2007). Detailed modelling of this transition using the conditions required for 1720-MHz OH maser production with both C-type and J-type shocks indicate that the time at which the appropriate gas density is reached ($\sim 10^5$ cm$^{-3}$), the gas temperature has cooled too much (to 15 K from required 300–600 K) to be able to generate the necessary H$_2$O column density (Woodall & Gray 2007).

5 CONCLUSION

Radio and infrared observations towards G349.7+0.2, an SNR with associated OH(1720 MHz) masers, were used to investigate the interaction of the SNR with the adjacent molecular cloud. The main results are summarized below.

(i) Emission from several molecular species ($^{12}$CO, $^{13}$CO, CS, HCO$^+$, HCN, H$_2$CO and SO) have been detected towards the SNR at the OH(1720 MHz) maser velocities. The molecular lines have moderate linewidths ($\approx 4$ km s$^{-1}$), showing no kinematic evidence of shock, but the derived gas density of $\approx 10^5$ cm$^{-3}$ and temperature of $\approx 45$ K are consistent with the predictions for OH(1720 MHz) maser production in molecular gas triggered by an SNR shock.

(ii) Molecular abundances of the shocked molecular gas in G349.7+0.2 are found to be somewhat different from those in another well-studied SNR, IC 443. The abundances of molecules such as CS, HCN and H$_2$CO are not enhanced by the effect of the shock, as expected from the most plausible models. The abundances of HCO$^+$ and SO appear to be an order of magnitude higher than in dark clouds. No SiO emission was detected, but the upper limit to the SiO column density does allow the possibility of an enhanced SiO abundance.

(iii) Strong H$_2$ emission was detected towards the SNR. Its distribution coincides with the bright radio shell and the location of
the OH masers, supporting the proposal that the H$_2$ emission arises from the SNR shock expanding into the adjacent molecular cloud. The total H$_2$ line luminosity in the source is very large, $\approx 5 \times 10^3 \, L_\odot$, which indicates that the interaction of SNRs with molecular clouds can produce H$_2$ line emission greater than that associated with fluorescent emission around massive star-forming complexes. This should be born in mind when interpreting extragalactic H$_2$ line emission.

(iv) In G349.7+0.2 we have clear observational evidence of an extended OH cloud associated with shocked regions in the SNR, as revealed by thermal absorption against the SNR continuum emission. The distribution of the OH gas correlates well with the OH(1720 MHz) maser locations and the distribution of shocked H$_2$. An upper value for the OH fractional abundance ($\sim 10^{-6}$) is greater than for cold clouds and is consistent with predictions for water dissociation by a soft X-ray flux from the SNR. We found no H$_2$CO absorption towards the SNR.

(v) We detected for the first time OH main-line maser emission at 1665 and 1667 MHz in directions towards and near G349.7+0.2. Only a 1665-MHz maser is located towards the SNR and was identified with an IR source SSTGLMC G349.7294+00.1747 from the GLIMPSE Catalogue. The other maser was detected in both main-line transitions and coincides with the ultracompact H II region IRAS 17147–3725, located southeast of the SNR. We also found weak H$_2$CO absorption towards this H II region. No masing was detected towards the SNR from excited-state OH transitions around 4.8 and 6 GHz, nor from the 6 GHz CH$_3$OH transition.

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