OH(1720 MHz) Masers As Signposts of Molecular Shocks

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ABSTRACT

We present observations of molecular gas made with the 15-m James Clark Maxwell Telescope toward the sites of OH(1720 MHz) masers in three supernova remnants: W 28, W 44 and 3C 391. Maps made in the $^{12}\text{CO} \ J = 3 - 2$ line reveal that the OH masers are preferentially located along the edges of thin filaments or clumps of molecular gas. There is a strong correlation between the morphology of the molecular gas and the relativistic gas traced by synchrotron emission at centimeter wavelengths. Broad CO line widths ($\Delta V = 30$-50 km s\textsuperscript{-1}) are seen along these gaseous ridges, while narrow lines are seen off the ridges. The ratio of H$_2$CO line strengths is used to determine temperatures in the broad-line gas of 80 K, and the $^{13}\text{CO} \ J = 3 - 2$ column density suggests densities of $10^{4}$-$10^{5}$ cm$^{-3}$. These observations support the hypothesis that the OH(1720 MHz) masers originate in post-shock gas, heated by the passage of a supernova remnant shock through dense molecular gas. From the observational constraints on the density, velocity and magnetic field we examine the physical properties of the shock and discuss the shock-production of OH. These OH(1720 MHz) masers are useful “signposts”, which point to the most promising locations to study supernova remnant/molecular cloud interactions.

Subject headings: ISM: supernova remnants, molecules – ISM: individual (W28, W44, 3C391) – masers

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1. Introduction

It has recently been argued that a satellite line ($\nu_0 = 1720.53$ MHz) from the ground state of the hydroxyl radical (OH) is a powerful tracer for studying the interaction of supernova remnant shocks with molecular clouds (Frail, Goss & Slysh 1993). Bright OH(1720 MHz) maser emission has been detected towards 17 supernova remnants (10% of the observed sample) in our Galaxy (Green et al. 1997). On the basis of this positional and velocity coincidence the case can be made that the OH(1720 MHz) masers in supernova remnants are a separate class of OH masers in our Galaxy, distinct from the OH masers in star-forming regions and those in the circumstellar shells of late-type stars.

Both observationally and theoretically there is support for the hypothesis that the masers are collisionally excited by H$_2$ heated by the passage of a shock. Early theoretical work by Elitzur (1976) showed that collisions of OH with H$_2$ can create a strong inversion of the 1720 MHz line for a range of kinetic temperatures ($25 \leq T_k \leq 200$ K) and molecular gas densities ($10^3 \leq n_{H_2} \leq 10^5$ cm$^{-3}$) which are typical of the conditions expected in cooling post-shock clouds. Pavlakis & Kylafis (1996a,b) have included the effects of far infrared line overlap (due to thermal and turbulent motions) and used newly computed collisional cross sections between OH and H$_2$ to confirm Elitzur’s basic result for a limited range of $T_k=100$ to 200 K.

The observational evidence that the OH(1720 MHz) masers originate in the post-shock gas is less compelling, relying mostly on indirect and morphological indicators (see Green et al. 1997). What is missing for the most part are clear kinematic and chemical signatures of a molecular shock in the vicinity of the OH(1720 MHz) masers. This situation has begun to change. For the well-studied IC 433 there is a clear kinematic shock signature at the location of the masers (van Dishoeck, Jansen & Phillips 1993), and for W 44 and 3C 391 Reach and Rho (1996) detected local emission maxima for the important cooling line of [OI] at the location of several OH(1720 MHz) masers. In this paper we detail a molecular line study undertaken toward the sites of several OH(1720 MHz) masers with the aim of testing whether they originate in post-shock molecular gas.

2. Observations

The observations were made over 4 nights from 1997 July 20 to 23 using the 15-m James Clark Maxwell Telescope (JCMT). We made $^{12}$CO $J = 3 - 2$ raster maps around four OH(1720 MHz) maser sites toward three supernova remnants: W 28, W 44 and 3C 391. The mapped regions in W 28 and W 44 are designated as W 28F, W 44E and W 44F in Claussen et al. (1997), while for 3C 391 we mapped the region around the southernmost maser (Frail et al. 1996). Details are given in Table 1.

At several of the intensity peaks found in the CO maps, we obtained spectra of a number of other molecules. These observations and results will be discussed in detail in a subsequent paper.
Here we make use only of the $^{13}$CO $J = 3 - 2$ (330.588 GHz), H$_2$CO $3_{03}$-$2_{02}$ (218.222 GHz), H$_2$CO $3_{22}$-$2_{21}$ (218.475 GHz), and H$_2$CO $5_{05}$-$4_{04}$ (362.736 GHz) transitions. The $3 - 2$ transitions of H$_2$CO required the facility A-band receiver, with a beamwidth of 20" and a main beam efficiency of 0.79.

3. Results

In Plates 1 and 2 we show maps of integrated CO $J = 3 - 2$ emission together with representative spectra at several locations. The maser positions are also superimposed on these maps. The velocity data cubes of these pointings show a rich variety of complex structure, but we will defer a detailed discussion of these for another paper. Here we present evidence which indicates the existence of molecular shocks in the vicinity of the OH(1720 MHz) masers.

It is apparent in Plates 1 and 2 that the masers are not located at random with respect to the molecular gas but rather are found near the peaks in the integrated CO $J = 3 - 2$ maps. In one striking example the line of nine masers in W 44E nicely delineates the forward edge of the molecular gas, closest to the shock. Claussen et al. (1997) have suggested that this line of masers traces the shock front from W 44 which is moving eastward into the ambient molecular gas. The morphology of this gas is also noteworthy as it is concentrated in well-defined filaments or clumps. These features are largely unresolved by our 13" beam in one dimension but are 1 pc to 2 pc long in the other. In W 44F, for example, a thin filament of gas can be traced from the northwest to the southeast across the entire 70" × 75" map. It is likely that the true extent of these features is not revealed by these figures since we have mapped only a small fraction (< 1%) of each supernova remnant. With few exceptions, the masers are preferentially located nearer to the edge of the shock (as traced by the non-thermal emission) than the peak of the CO itself. This suggests that some special conditions are required in order to produce a strong inversion of the OH molecule.

Another interesting correlation can be discerned between the integrated CO $J = 3 - 2$ maps and the radio continuum images found in Claussen et al. (1997) and Wilner et al. (1998). Near W 44F the radio continuum contours have the same orientation as the molecular filament and a local maxima in the non-thermal radio continuum of W 44F coincides with the peak in the CO $J = 3 - 2$ map. Likewise, for 3C 391 the radio continuum and the molecular clump have the same curvature while for W 28F a prominent "kink" can be seen in in both the molecular gas and the radio continuum. Local increases in the synchrotron emissivity do not require new particle acceleration, but rather can originate from the compression of the magnetic field and existing relativistic electrons in a radiative shock (Blandford & Cowie 1982). While good correlations have been noted between the optical line and radio continuum emission of several supernova remnants (e.g. Cygnus Loop: Straka et al. 1986), this is the first clear signature to our knowledge of a synchrotron/molecular correlation.

Although the morphology of the molecular gas is suggestive of a shock interaction, it is the velocity extent of the lines that are the most telling. Spectra taken near the peaks and along
the ridges of the integrated CO $J = 3 - 2$ emission (see Figs. 1 and 2) consistently show broad, asymmetric lines whose widths ($\Delta V = 30 - 50$ km s$^{-1}$), reminiscent of those seen toward IC 433 (van Dishoeck et al. 1993). Away from the bright peaks the line widths narrow considerably ($\Delta V \leq 10$ km s$^{-1}$) (e.g. Fig. 1). Moreover, whenever it is possible to identify this less disturbed gas, its LSR velocity agrees with that of any nearby masers to within a few km s$^{-1}$. Examples include 3C 391 where a narrow line component in CO emission at $+105.5$ km s$^{-1}$ is found widely distributed in the region which includes the OH(1720 MHz) maser at $104.9$ km s$^{-1}$ (see also Reach and Rho 1998). In W 44E and W 44F there are what appear to be narrow, self-absorption features at $+43$ and $+46$ km s$^{-1}$, respectively. Although they too are close to the mean LSR velocity of the masers in each direction, some caution is warranted since false absorption may be introduced by our sky switching calibration cycle. The correspondence between the maser velocities and colder, presumably unshocked ambient medium is expected since it has been argued elsewhere (Claussen et al. 1997) that these masers originate in shocks which are viewed largely transverse to the line of sight.

For the bright CO peak at (15$''$, $-40''$) in the W 28F map (Plate 1), we have also observed the three H$_2$CO transitions $3_03-2_02$, $3_{22}-2_{21}$, and $5_{05}-4_{04}$ to determine both gas kinetic temperature and gas density. The importance of H$_2$CO in measuring $T_k$ and $n$ is described in detail in Mangum & Wootten (1993). The intensity ratio $3_{03}-3_{02}/3_{22}-3_{21}$ provides the gas kinetic temperature, either from LVG analysis (e.g. Mangum & Wootten 1993; van Dishoeck et al. 1993) or using LTE expressions (Mangum & Wootten 1993). The observed intensity ratio in W 28F is 3.25, implying $T_k = 80 \pm 10$ K. This high value of $T_k$ is further evidence of a shock. When $T_k$ is known, the ratio $3_{03}-2_{02}/5_{05}-4_{04}$ provides the gas density. With $T_k = 80$ K, we interpolated between LVG models of Mangum & Wootten (1993), using the observed 3-2/5-4 ratio of 1.5 to find $n_{H_2} = 2 \times 10^6$ cm$^{-3}$.

We have $^{13}$CO $J = 3 - 2$ spectra at $^{12}$CO intensity peaks in W 28F, W 44E, and 3C 391. Because the critical density for excitation of CO is low, level populations probably follow a Boltzmann distribution. Assuming LTE, it is straightforward to obtain from the line ratio $^{12}$CO/$^{13}$CO the optical depth, the excitation temperature, and the CO column density (e.g. Mitchell et al. 1992). The observed beam-averaged column densities yield a gas number density if we know the line-of-sight extent of the gas. On the assumption that the gas in the beam has an extent of one beamwidth, typical gas densities of $n_{H_2} = 10^4 - 10^5$ cm$^{-3}$ are found.

4. Discussion

These JCMT observations have demonstrated that the OH(1720 MHz) masers in W 44E, W 44F, W 28F and 3C 391 are located near local peaks in the integrated CO $J = 3 - 2$ emission. This hot, dense molecular gas is organized into thin filaments or clumps, with the long axis perpendicular to the shock normal (as inferred from the radio continuum), suggesting compression of the gas by a passing shock. We deduce the existence of the shock from the large observed velocity extent ($\Delta V = 30 - 50$ km s$^{-1}$) and the high measured temperature of 80 K. These observations lend
important support to the hypothesis that the OH(1720 MHz) masers originate in the molecular gas behind the shock. We will now attempt to infer the physical properties of the post-shock gas, determine the character of the shock, and investigate models for the shock production and excitation of OH.

In a radiative shock the shock velocity $V_s$ is small enough or the ambient gas density $\rho_0$ is large enough that the timescale for the gas to radiate away its thermal energy, acquired by the passage of the shock, is short compared to the dynamical time of the shock itself (Draine & McKee 1993). The amount of compression expected in this post-shock gas depends in large measure on the strength of the initial magnetic field $B_0$. The magnetic pressure dominates over the thermal pressure and therefore $\rho_{ps}/\rho_0=\sqrt{2}V_s/V_A$, where $V_A$ is the Alfvén velocity in the ambient gas. It has been customary to estimate $B_0$ using an empirical relation between $B$ and number density $n$ (e.g. Fiebig & Güsten 1989), which shows that over at least 8 orders of magnitude in density $B(\mu G) = \sqrt{n (cm^{-3})} \mu G$ and implies that $V_A \approx 1.84$ km s$^{-1}$. Such a relation is not unexpected if there is rough equilibrium between the kinetic and magnetic energy densities in molecular clouds (Myers & Goodman 1988). However, the large observed scatter makes it unreliable to use in individual cases.

The OH(1720 MHz) maser line allows a unique measurement to be made of the strength of the line-of-sight magnetic field $B_{los}$ in the post-shock gas using the Zeeman effect (Claussen et al. 1997). In W 44 and W 28 Claussen et al. (1997) derived an average $B_{los}=200 \mu G$ which was remarkably constant in both direction and strength across each remnant. The large scale distribution of magnetic field vectors toward W 44 (Kundu & Velusamy 1972) as traced by the radio synchrotron emission is also uniform. This suggests that these $B_{los}$ values are not some peculiar local values, valid only in the vicinity of the masers, but rather they represent some global measurement in the post-shock magnetic field. For a randomly oriented field, the median value of the total magnetic field strength is $2B_{los}$ and therefore in W 44 and W 28 the post-shock magnetic field $B_{ps}=400 \mu G$, and the magnetic pressure $B^2_{ps}/8\pi = 6.4 \times 10^{-9}$ erg cm$^{-3}$, or alternatively (see below) $2.7 \times 10^5$ cm$^{-3}$ (km s$^{-1}$)$^2$.

The magnetic pressure dominates over all other sources of pressure in the post-shock gas, balancing the ram pressure of the gas entering the shock wave $\rho_0 V_s^2$. Thus a measurement of $B_{los}$ fixes a line in the $n_0-V_s$ plane which constrains the properties of the post-shock gas from which the OH(1720 MHz) masers originate. In practice there is sufficient uncertainty in $B_{ps}$ that we will consider shocks with a range of ram pressures over $10^5$ to $10^6$ cm$^{-3}$ (km s$^{-1}$)$^2$. Broadly speaking there are two classes of solutions allowed, a dissociative J-shock and a non-dissociative C-shock (Draine & McKee 1993). In a J-shock (for $V_s > 25$-45 km s$^{-1}$) the physical conditions change abruptly across the shock and molecules can be destroyed. In a C-shock the ions, drifting ahead of the neutrals, produce a more gradual transition and a thicker heating region with limited dissociation of molecules.

If we make the standard assumption that the observed CO $J = 3 - 2$ line widths $\Delta V$ of...
30-50 km s\(^{-1}\) are giving the shock velocity \(V_s\), then from our ram pressure constraint we infer \(n_o \approx 10^2 - 10^3\) cm\(^{-3}\). The final compression in the post-shock gas will depend on \(V_A\) in the ambient gas but for the value given above \(n_{ps} \approx 10^4\) cm\(^{-3}\). At these relatively low densities the shock is likely to be a dissociative J-type (Draine et al. 1983). A significant column of OH can be formed in the post-shock gas in such a shock (Neufeld & Dalgarno 1989) but the final column density of \(\text{H}_2\) never gets sufficiently high to prevent the eventual destruction of the OH by UV photons from the leading edge of the shock. This might explain why the OH masers appear to be confined along the leading edge of the integrated CO maps (see §3). There may be a small region behind the shock where the density and temperature of the OH is sufficient to produce \(\text{OH}(1720\ MHz)\) maser emission, while further downstream the OH is photodissociated.

Another alternative that satisfies our ram pressure constraint would be a slow, non-dissociative C-type shock propagating into denser gas. The true \(V_s\) could be smaller than the observed linewidths if the 13\(^{\prime\prime}\) beam intersected several shocks along the line-of-sight. Furthermore, the detection of \(\text{H}_2\text{CO}\) at the peaks of the integrated CO maps requires the presence of high density post-shock gas \(n_{ps} \approx 10^5 - 10^6\) cm\(^{-3}\). Theoretical models (Draine, Roberge & Dalgarno 1983, Kaufman & Neufeld 1996) show that significant columns of warm (\(T_k >1000\) K) OH are produced for \(V_s >15\) km s\(^{-1}\) at a few\(\times10^{16}\) cm behind the leading edge of the disturbance. However, as the gas cools to \(T_k \sim 400\) K the models predict that virtually all of the atomic oxygen not tied up in CO will be rapidly converted to \(\text{H}_2\text{O}\). Wardle, Yusef-Zadeh & Geballe (1998) suggested a novel solution to this problem, dissociating the \(\text{H}_2\text{O}\) by the soft X-rays emitted by the hot gas interior to the remnant. The X-rays penetrate into the dense water-rich gas producing OH in a small region (\(\sim 10^{15}\) cm) over which \(T_k \sim 100-200\) K. We consider the Wardle et al. (1998) model to be a particularly promising one since it would explain the apparent narrow region over which we find the OH masers (with respect to the molecular gas) and our measured \(T_k\) value.

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Table 1 – Telescope Pointing Parameters for CO $J = 3 - 2$ Mapping

<table>
<thead>
<tr>
<th>Name</th>
<th>RA(B1950) (h m s)</th>
<th>Dec(B1950) ($^\circ$ ' ″)</th>
<th>$V_{\text{LSR}}$ km s$^{-1}$</th>
<th>Ref. ($''$ ', '')</th>
<th>Raster ($''$ × '')</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 28F</td>
<td>17 58 49.2</td>
<td>−23 19 00.0</td>
<td>12</td>
<td>0,−1200</td>
<td>75×110</td>
</tr>
<tr>
<td>3C 391</td>
<td>18 46 47.7</td>
<td>−01 01 00.0</td>
<td>105</td>
<td>−120,120</td>
<td>80×80</td>
</tr>
<tr>
<td>W 44E</td>
<td>18 53 57.0</td>
<td>+01 25 45.0</td>
<td>45</td>
<td>−760,−1440</td>
<td>75×120</td>
</tr>
<tr>
<td>W 44F</td>
<td>18 54 04.7</td>
<td>+01 22 35.0</td>
<td>45</td>
<td>−760,−1440</td>
<td>70×105</td>
</tr>
</tbody>
</table>

Note. — (1) The facility SIS receiver (B3) was used at a center frequency of 345.796 GHz and the signal was fed into a digital autocorrelation spectrometer for a bandwidth of 500 MHz and channel spacing of 378 kHz (0.3 km s$^{-1}$). (2) The raster maps were made by driving the telescope in right ascension and integrating for 3 seconds at each position separated by 5″. (3) Sky subtraction was effected by observing a reference position after each row. (4) The beamsize at this frequency is 13″ and the main beam efficiency is 0.62.
Plate 1.— (left) A 75″×110″ map of $^{12}$CO $J = 3 - 2$ towards a region of OH(1720 MHz) masers known as W 28F. The masers locations are indicated by the filled red circles. The spectra are integrated over the bulk of the emission from −20 km s$^{-1}$ to +40 km s$^{-1}$. The color wedge on the right hand side of the plot is the velocity-integrated antenna temperature in units of K km s$^{-1}$. The shock front, determined from the centimeter radio continuum, lies toward the east. (right) Similar to W 28F but of a 75″×120″ region toward W 44E. The spectra are integrated from +20 km s$^{-1}$ to +38 km s$^{-1}$. The shock front lies toward the north east. At the assumed distance of 3 kpc for both W 28 and W 44 the 13″ beam has a spatial resolution of 0.2 pc.

Copies of this plate can be found at http://www.nrao.edu/~dfrail/jcmt_plate1.gif
Plate 2.— (top) Similar to Plate 1 but of a 80″×80″ region toward 3C391. The spectra are integrated from +60 km s\(^{-1}\) to +150 km s\(^{-1}\). The shock front lies toward the south west. At the assumed distance of 7.2 kpc for 3C391 the 13″ beam has a spatial resolution of 0.45 pc. (Bottom) Similar to 3C391 but of a 75″×105″ region toward W44F. The spectra are integrated from +49 km s\(^{-1}\) to +60 km s\(^{-1}\). The shock front lies toward the north east.

Copies of this plate can be found at http://www.nrao.edu/~dfrail/jcmt_plate2.gif
Figure 1.— Sample spectra taken from the $^{12}$CO $J = 3 - 2$ map of 3C 391 (Plate 2) at the peaks of the narrow line and broad line emission areas (see main text). These peaks are offset from the map center by $(20'', -25'')$ and $(0'', 10'')$, respectively. The OH(1720 MHz) masers velocity is $+104.9$ km s$^{-1}$. The line brightness on the vertical axis is expressed as antenna temperature $T_A^*$. 
Figure 2.– Sample spectra from the integrated \(^{12}\)CO \(J = 3 - 2\) maps of W28F, W44E and W44F. The spectra are taken towards the peaks at position offsets from the center of each map of \((0'', -10'')\), \((-10'', -5'')\) and \((15'', -40'')\), respectively. The pseudo absorption features are likely artifacts produced by emission in the reference position. The average OH(1720 MHz) maser velocities for W28F, W44E and W44F are +11.0 km s\(^{-1}\), +44.7 km s\(^{-1}\), and +46.6 km s\(^{-1}\), respectively.
REFERENCES


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