A MODEL FOR OH(1720 MHz) MASERS ASSOCIATED WITH SUPERNOVA REMNANTS, AND AN APPLICATION TO SGR A EAST

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ABSTRACT

OH(1720 MHz) masers unaccompanied by 1665/7 MHz line masers have recently been proposed as indicators of the interaction of supernova remnants (SNRs) and molecular clouds. We present a model for the masing region in which water produced in a C-type shock wave driven into the molecular cloud is dissociated as a result of the X-ray flux from the SNR. We note that the magnetic field strengths inferred from Zeeman splitting of the 1720 MHz line measure the internal pressure of the supernova remnant.

In addition, we discuss the interaction of Sgr A East, a SNR candidate, with the 50 km/s cloud at the Galactic Centre and present near-infrared observations of H$_2$ emission towards the regions where OH(1720 MHz) maser emission is concentrated. The magnetic field strength obtained from earlier Zeeman measurements is consistent with rough pressure equilibrium between the postshock gas and the X-ray gas filling Sgr A East detected by ASCA. Further, the intensity of the v=1–0 S(1) line of H$_2$ is consistent with the shock strength expected to be driven into the molecular gas by this pressure. The relative intensities of the H$_2$ lines in Sgr A East imply mainly collisional excitation.

Subject headings: Galaxy: center – ISM: individual (Sgr A East) – masers – molecular processes – shock waves – supernova remnants

1. INTRODUCTION

OH masers have generally been used as a diagnostic for HII regions and evolved stars. However, a recent study by Frail, Goss & Slysh (1994) revealed that the 1720 MHz transition of OH maser emission, when unaccompanied by the 1665 and 1667 MHz OH lines, can be an effective indicator of shock waves interacting with molecular clouds, particularly for supernova remnants (SNRs). Frail et al. (1994) detected 26 distinct OH(1720 MHz) maser spots along the interface between the SNR W28 and an adjacent molecular cloud. Evidence of the association between the molecular cloud and W28 comes from the distribution of the molecular material following the eastern edge of the supernova shell (Wootten 1977). There are more than a dozen Galactic sources and three extragalactic sources in which 1720 MHz OH masers have been found interior to SNR’s with adjacent molecular clouds (Yusef-Zadeh, Uchida & Roberts 1995; Frail et al. 1996; Yusef-Zadeh et al. 1996; Green et al. 1997; Seaquist, Frayer & Frail 1997). These masers are close both in position and velocity to the interfaces between the remnants and the clouds. In addition, in several of these sources, CO emission lines reach a maximum in both brightness and linewidth at the interface between remnant and cloud (Wootten 1977). These are strong observational indications that the shocks are caused by the remnants expanding into their respective adjacent molecular clouds.

Further support is provided by theoretical studies of the pumping of the OH maser lines (Elitzur 1976; Pavlakis & Kylafis 1996a,b). The 1665 and 1667 MHz masers are pumped by far-infrared radiation and are therefore associated with HII regions and evolved stars. The OH(1720 MHz) maser is collisionally pumped in molecular gas at temperatures and densities between 15-200 K and 10$^4$ – 10$^6$ cm$^{-3}$,
respectively. Thus in the absence of the 1665/7 MHz transitions, the OH 1720 MHz line presumably traces cooling, shocked gas.

However, shock chemistry predicts that OH is not abundant in the postshock gas as it is rapidly converted to H$_2$O within the shock front. OH masers adjacent to compact HII regions are produced by photodissociation of H$_2$O (Elitzur & de Jong 1978; Hartquist & Sternberg 1991; Hartquist et al. 1995), but in that case there is a strong dissociating FUV flux from the star. The dissociating flux is largely absorbed and reradiated in the FIR by grains, providing a sufficient IR background to also pump the 1665/7 MHz transitions (e.g. Pavlakis & Kylafis 1996b). This cannot be the case for the unaccompanied 1720 MHz masers associated with SNR-molecular cloud interactions.

Here we propose that it is the weak X-ray flux from the SNR interior that is ultimately responsible for the dissociation of H$_2$O in the shocked molecular gas. We note that if the OH maser arises in the postshock gas, then Zeeman measurements determine the magnetic field strength in the postshock gas, and thus measure the pressure within the SNR more directly than other methods. The observations of the IC 443, W28 and W44 are consistent with this scenario. Finally, we apply these ideas to the interaction of the Galactic center nonthermal source Sgr A East, which is either a SNR or a multiple-SNR driven bubble, with a molecular cloud at the Galactic center.

2. A MODEL FOR THE PRODUCTION OF OH

Although the pumping conditions for the 1720 MHz OH masers suggest that the masers are associated with shock waves, this is not an immediate consequence of shock chemistry (e.g. Draine, Roberge & Dalgarno 1983; Hollenbach & McKee 1989). In J-type shock waves molecules are destroyed within the shock front and reform well downstream of the hot, ionised gas immediately behind the shock. OH exists as an intermediary in the incorporation of oxygen into water, at a temperature of roughly 400 K, too high to explain the 1720 MHz masers. C-type shocks are non-dissociative, and efficiently convert the atomic and diatomic oxygen in the unshocked gas to H$_2$O if the shock velocity exceeds 10 km s$^{-1}$ (Draine et al. 1983; Kaufman & Neufeld 1996). Once the gas temperature exceeds about 400 K, OH is rapidly formed by the endothermic reaction

$$O + H_2 \rightarrow OH \quad (1)$$

but is even more rapidly converted to water by the less-endothermic reaction

$$OH + H_2 \rightarrow H_2O. \quad (2)$$

Thus shock waves do not of themselves produce significant columns of OH.

The production of a significant abundance of OH in the postshock gas requires dissociation of H$_2$O. Although this can be achieved by intense UV irradiation of the molecular gas (Hartquist & Sternberg 1991), the resultant grain heating generates a FIR continuum capable of pumping the 1665 and 1667 MHz transitions (Pavlakis & Kylafis 1996b) and cannot explain the OH(1720 MHz) masers associated with supernova remnants. In addition, the emission from the molecular clouds associated with the remnants do not show signatures of UV heating (e.g. Burton et al. 1990; Reach & Rho 1996).

However, dissociation can occur because of the irradiation of the molecular cloud by X-rays produced by the hot gas in the interior of the adjacent SNR. The dissociation occurs indirectly: electrons are photoejected by the X-rays and collisionally excite the Werner Ly-α band of H$_2$. The subsequent radiative decay contributes to a secondary dissociating FUV radiation field. Irradiation by X-rays is more efficient at heating, ionising and dissociating the gas rather than heating grains as the ratio of the grain to molecule absorption cross-sections for X-rays is much lower than for UV photons (Maloney, Hollenbach & Tielens 1996). X-rays are much more penetrating than UV, and the dissociating flux, although weak, is generated throughout the cloud.

This suggests a model in which water forms within a C-type shock front and is subsequently dissociated by the secondary FUV flux permeating the cloud as the shocked gas cools behind the shock front, as sketched in Fig. 1. The upper portion of the figure shows the velocity field and magnetic field lines for a perpendicular C-type shock being driven into a molecular cloud adjacent to the SNR. The distinct physical regions delineated by the species containing the oxygen that is not locked up in CO are indicated in the lower part of the Figure. The preshock gas, at the right of Fig. 1 is at rest, and the oxygen that is not bound in CO exists in atomic or diatomic form. As the gas is accelerated, compressed, and heated within the shock front, the atomic and molecular oxygen is rapidly converted to H$_2$O by reactions (1) and (2) (Draine et al. 1983; Kaufman & Neufeld 1996). The peak temperature within the shock is typically of order 1000 K. The shocked gas cools as it drifts behind the shock front. The entire structure is subject to the weak dissociating flux produced by the X-rays permeating the cloud. At high temperatures the dissociation cannot compete with the OH and H$_2$O formation reactions (1) and (2). However, the temperature behind the shock eventually drops to the point where the reaction rates for formation are so
Fig. 1.— A sketch of the model for the production of OH in molecular clouds associated with supernova remnants. A C-type shock is driven into a molecular cloud adjacent to a SNR. The X-ray flux from the SNR interior (to the left) permeates the cloud, inducing a weak secondary FUV flux that is produced locally throughout the cloud. The shock efficiently wave incorporates atomic oxygen into water. Once the the shocked gas cools below 180 K it is subsequently dissociated to OH and then to OI by the secondary UV flux (see text).

slow that dissociation proceeds, and there is a warm layer which is rich in OH.

The analogous scenario for J-type shock waves fails because the water abundance $n(\text{H}_2\text{O})/n_\text{H}$ in the cooling postshock gas exceeds $10^{-5}$ only for preshock densities in excess of $10^6$ cm$^{-3}$ (Elitzur, Hollenbach & McKee 1989), and the emission from the immediate postshock gas is largely absorbed and reradiated in the FIR by grains (Hollenbach & McKee 1989), creating a radiation field that is strong enough to pump the OH 1665/7 MHz transitions.

Here we show that the X-ray flux from the SNR incident on the water-rich gas behind a C-type shock wave produces a sufficient column of OH at the correct temperature and abundance to satisfy the pump conditions. The physical state of X-ray irradiated gas is determined by the local heating rate, which can be represented by the parameter

$$\xi_{\text{eff}} \approx 1.3 \times 10^{-6} \frac{100 F_X}{n_5 N_{22}}$$

(Maloney et al. 1996) where $F_X$ is the flux incident on the cloud surface (erg cm$^{-2}$ s$^{-1}$), $n_5 = n_5 10^5$ cm$^{-3}$ is the gas density and $N_{22} = N_{22} 10^{22}$ cm$^{-2}$ is the attenuating column to the cloud surface. $F_X \approx L_X/4\pi R_P^2 \approx 0.01 L_{36} R_{pc}^{2}$, where $L_X = L_{36} 10^{36}$ erg s$^{-1}$ is the SNR X-ray luminosity, and $R_{pc}$ is the SNR radius in pc, so typically $F_X \sim 0.01$ erg cm$^{-2}$ s$^{-1}$, and $\xi_{\text{eff}} \approx 10^{-6}$.

The dissociation rates for H$_2$O and OH are

$$R_{\text{H}_2\text{O}} \approx 8.4 \times 10^{-12} n_5 \left( \frac{\xi_{\text{eff}}}{10^{-6}} \right) \text{ s}^{-1}$$

and

$$R_{\text{OH}} \approx 4.4 \times 10^{-12} n_5 \left( \frac{\xi_{\text{eff}}}{10^{-6}} \right) \text{ s}^{-1}$$

per molecule respectively (Maloney et al. 1996). Thus the dissociation timescale for H$_2$O is $\sim 10^{10}$ s, comparable to the cooling time scale for the gas behind a C-type shock wave. If the temperature is too high the dissociation of H$_2$O is counteracted by rapid reformation via reaction (2) which has a rate per OH molecule

$$k(T) = 6.5 \times 10^{-13} n_5 T^{1.95} \exp \left( \frac{-1420}{T} \right) \text{ s}^{-1}.$$

(6)

where $T$ is in Kelvin (Wagner & Graff 1987). The dissociation of H$_2$O does not proceed in the postshock gas until the temperature drops to a value $T_{\text{OH}}$ for which $k \approx R_{\text{H}_2\text{O}}$, that is

$$T_{\text{OH}} \approx 175 \left[ 1 - 0.28 \log \left( \frac{\xi_{\text{eff}}}{10^{-6}} \right) \right]^{-1} \text{ K}.$$  (7)

This critical temperature is weakly-dependent on the X-ray flux because of the temperature sensitivity of reaction (3). Once this point is reached, the dissociation of H$_2$O to OH and subsequently to OI proceeds. As the dissociation rate of OH is roughly half that of H$_2$O there will be a column of OH with $x_{\text{OH}} \approx 10^{-4} - 10^{-5}$ and $T \approx 100$–200 K extending over a distance of about $10^{15}$ cm.

This model naturally produces the correct conditions for the collisional pumping of the OH 1720 MHz transition when SNRs interact with molecular clouds. It implies that Zeeman observations of the 1720 MHz transition measure the magnetic field in the postshock gas. As the magnetic pressure dominates the thermal and ram pressures behind the C-type shock, and the postshock gas is in near pressure equilibrium with the SNR interior, Zeeman measurements give a good estimate of the pressure within the SNR.
IC443, W28 and W44 all show evidence of shocked molecular gas (Wootten 1977, 1981; Dickman et al. 1992) and, in the case of IC443 and W44, a contribution to line emission from C-type shock waves (Burton et al. 1990; Wang & Scoville 1992; Reach & Rho 1996). Claussen et al. (1997) used Zeeman splitting in the OH(1720 MHz) line to obtaining line-of-sight field strengths $B_\parallel$ of roughly 0.3 milliGauss for the masers in W28 and W43, and showing that the field strength determinations are consistent with the pressures inferred by other means, such as the velocity of Hα filaments. The X-ray luminosities for these three SNRs imply incident X-ray fluxes of order 0.01 erg cm$^{-2}$ s$^{-1}$ (Asaoka & Aschenbach 1994; Rho et al. 1994, 1996).

3. H$_2$ 2$\mu$m EMISSION ASSOCIATED WITH SGR A EAST

The nonthermal radio source Sgr A East is thought to be a SNR lying roughly 30 pc behind the Galactic center (Yusef-Zadeh & Morris 1987; Pedlar et al. 1989). The recent discovery of OH(1720 MHz) masers, unaccompanied by maser emission at 1665 and 1667 MHz, at the interface of the 50 km s$^{-1}$ molecular cloud (M-0.02-0.07; Mezger et al. 1989) and Sgr A East provides strong evidence that these two are physically interacting with each other (Yusef-Zadeh et al. 1996). The maser spots surrounding the Sgr A East shell have velocity close to the systemic velocity of the SNR near 50 km s$^{-1}$, and Yusef-Zadeh et al. argued that the expansion of a supernova into the Sgr A East molecular cloud (i.e. the 50 km s$^{-1}$ cloud) and cloud-cloud collisions are responsible for the OH(1720 MHz) maser emission.

Recently we used the long slit 1-5$\mu$m spectrometer, CGS4, at UKIRT to search for shocked H$_2$ emission associated with the OH (1720 MHz) masers seen towards Sgr A East. The 2.5$''$ wide slit of the spectrometer was placed along two prominent regions of Sgr A East where the masers are concentrated (see positions A to G in Figure 1 of Yusef-Zadeh et al. 1996). Flux calibration was obtained from an observation of BS 6310 and wavelength calibration was obtained from OH sky lines. The 1-0 S(1) line (2.122 $\mu$m) was detected toward both regions, with a flux in each row of the array of roughly 5 $\times$ 10$^{-19}$ W m$^{-2}$. Figure 2 shows spectra that were seen along positions A through G. The second row from the top coincides with position A OH maser at $\alpha$(1950) = 17$^h$42$^m$33.6$^s$, $\delta$(1950) = -29$^\circ$00$'$09.6$''$ at the interface of Sgr A East. The top row is 1.2 arcsec SW, and the third - 6th spectra are 1.2, 2.5, 3.7, and 4.9 arcsec to the NE of the above coordinates. In the individual spectra the 1-0 S(1) lines can be seen, but other lines of H$_2$ are too weak for them to be securely identified. The spectrum at the bottom of the figure is the average of the six spectra. In the averaged spectrum the 1-0 S(0) (2.223 $\mu$m) and 2-1 S(1) (2.248 $\mu$m) lines of H$_2$ are evident, as well as H I Br $\gamma$ (2.166 $\mu$m). The 2-1 S(1) / 1-0 S(1) and 1-0 S(0) / 1-0 S(1) line ratios are about 1/7 and 1/3 in the average spectrum.

The intensity ratios of these lines at the Galactic Center are often consistent with collisional excitation rather than fluorescence (Gatley et al. 1984; Burton & Allen 1992; Pak et al. 1996), but the high density of the molecular gas at the Galactic center and the intense UV radiation field in the region allow the line ratios from UV-irradiated gas to resemble those of shock-heated gas (Sternberg & Dalgarno 1989). While the UV radiation field is known to be strong in Sgr A West ($10^6$ G$_0$), the UV radiation field associated with Sgr A East is likely to be much less than in the inner pc of the Galaxy as Sgr A East probably lies roughly 30 pc behind Sgr A West (Pedlar et al. 1989) and the maser spots are distributed in an area free of the HII regions that would be associated with massive star formation. Given the weak detections of the 2-1 S(1) and 1-0 S(0) lines, the ratios of their intensities with that of the 1-0 S(1) line are consistent with those produced by collisional excitation (i.e. 1/10 and 1/4 respectively), although a fluorescent component arising in a lower density environment and producing line ratios of $\sim$ 1/2 and $\sim$ 2/3, respectively, may also contribute.

4. DISCUSSION

We have proposed a model for the OH 1720 MHz masers unaccompanied by main-line transitions that are associated with SNRs interacting with molecular clouds (Frail et al. 1994, 1996; Green et al. 1997). A C-type shock wave driven into the adjacent cloud produces water that is subsequently dissociated by the secondary FUV flux produced by the interaction of X-rays from the SNR incident on the molecular cloud. The dissociation only becomes significant once the shocked molecular gas has cooled to about 180 K, naturally producing OH at the temperature and abundance required for collisional pumping of the 1720 MHz transition.

Some consistency checks suggest that this model also applies to the OH 1720 MHz masers seen towards Sgr A East. Firstly, within the framework of the model the magnetic field strengths of roughly 3 mG inferred from Zeeman splitting of the OH masers (Yusef-Zadeh et al. 1996) are measurements of the magnetic pressure in the postshock gas, which dominates the gas pressure behind the shock front. Equating the magnetic pressure, $4\pi B^2/8\pi$, with $\rho v^2_s$, where $\rho$ is the preshock density and $v_s$ is the shock speed, and adopting a preshock density of
Fig. 2.— Six adjacent spectra, with vertical scales offset from one another, extracted from a CGS4 observation of the 1720 MHz OH maser spots in Sgr A East and (at the bottom) the averaged spectrum of the six. Each spectrum is of an area $1.2'' \times 2.5''$. See text for positions.

$n_H = 2 \times 10^4 \text{ cm}^{-3}$ (Mezger et al. 1989), we infer $v_s \approx 25\text{--}30 \text{ km s}^{-1}$. A C-type shock at this speed produces an intensity in the 1-0 S(1) line of $10^{-4}$--$10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Draine et al. 1983; Kaufman & Neufeld 1996). The measured intensity, after correcting for extinction assuming that $A_K \approx 2.5$, is $1.5 \times 10^{-4} \text{ erg s}^{-1} \text{ cm}^{-2}$. Second, the inferred post-shock pressure is comparable to the pressure of the X-ray emitting gas filling Sgr A East detected with ASCA (Koyama et al. 1996), which has $n_e \approx 6 \text{ cm}^{-3}$ and $T \approx 10 \text{ keV}$, and a pressure of $2 \times 10^{-7} \text{ erg cm}^{-3}$. Finally, we note that the X-ray luminosity from Sgr A East is $10^{36} \text{ erg s}^{-1}$ (Koyama et al. 1996), providing the required dissociating flux for the production of OH behind the shock front.

Rho (1995) suggests that centrally-peaked thermal X-ray emission from SNRs is characteristic of SNR-molecular cloud interactions. Green et al. (1997) note that all of the SNRs detected in the OH (1720 MHz) line that have been observed in X-rays are members of this class. Our model appears to strengthen this link by relying on the X-ray flux from the SNR to produce OH, but in principle a cosmic-ray flux enhanced by a factor of 100 over the solar neighbourhood value has a similar effect on the heating and chemistry of molecular gas (see, e.g. Maloney et al. 1996). The high-energy cosmic-ray flux in the W44, W28 and IC 443 SNRs inferred from EGRET observations is roughly two orders of magnitude larger than the solar neighbourhood value (Esposito et al. 1996), so a naive extrapolation down to the cosmic-ray energies important for ionisation suggests that the cosmic-ray and X-ray contributions to the secondary FUV flux may be similar.

In any case, this picture supports the suggestion by Frail et al. (1994) that the presence of the OH 1720 MHz line, and the absence of the 1665/1667 MHz lines provide a clear diagnostic of shocked molecular gas.

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