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Collisional excitation of OH(6049 MHz) masers in supernova remnant – molecular cloud interactions

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Abstract. OH (1720 MHz) masers serve as indicators of SNR – molecular cloud interaction sites. These masers are collisionally excited in warm (50–100 K) shocked gas with densities of order $10^5\,\mathrm{cm}^{-3}$ when the OH column density is in the range 10^{16}–$10^{17}\,\mathrm{cm}^{-2}$. Here I present excitation calculations which show that when the OH column density exceeds $10^{17}\,\mathrm{cm}^{-2}$ at similar densities and temperatures, the inversion of the 1720 MHz line switches off and instead the 6049 MHz transition in the first excited rotational state of OH becomes inverted. This line may serve as a complementary signal of warm, shocked gas when the OH column density is large.

Keywords. supernova remnants, molecular processes, radiation mechanisms: nonthermal, radio lines: ISM

The OH excitation calculations discussed here include the 32 lowest energy levels, with transition wavelengths and A values from Detombes *et al.* (1977) and Brown *et al.* (1982), and rates for collisional de-excitation by H_2 kindly provided by Alison Offer (private communication). Following Lockett & Elitzur (1989) and Lockett, Gauthier & Elitzur (1999), I adopt a uniform slab model for the masing medium. Radiative transfer is approximated using escape probabilities based on the mean optical depth, including the effects of line overlap. The slab is parametrised by density n_{H}, temperature T, column N_{OH}, velocity width, and a radiation field contributed by the CMB and warm dust.

Figs. 1 and 2 show results for $T = 50\,\mathrm{K}$, assuming small velocity gradients within the slab, and no far-infrared radiation from dust. These conditions are broadly consistent with warm gas that is cooling off behind a shock wave driven into a molecular cloud by an adjacent supernova remnant. Fig. 1 shows the maser optical depth through the slab for the 1720 MHz satellite line in the ground rotational state and its analogues in the first (6049 MHz) and second (4765 MHz) excited rotational states. At low OH column densities the 1720 MHz line is inverted, peaking in the range 10^{16}–$10^{17}\,\mathrm{cm}^{-2}$. At about $10^{17}\,\mathrm{cm}^{-2}$ the optical depth of the slab to the 1720 MHz line suppresses the inversion. Meanwhile the inversion in the 6049 MHz line grows, peaking at $N_{\mathrm{OH}} \approx 3 \times 10^{17}\,\mathrm{cm}^{-2}$ (similar results were found by Pavlakis & Kylafis 2000). The 4765 MHz line peaks at $N_{\mathrm{OH}} \sim 10^{18}\,\mathrm{cm}^{-2}$. The effect of varying n_{H} and N_{OH} is explored in Fig. 2. As expected, masing in the 1720 MHz line is strongest for $n_{\mathrm{H}} \sim 10^5\,\mathrm{cm}^{-3}$ and $N_{\mathrm{OH}} \sim 10^{16.5}\,\mathrm{cm}^{-2}$. The inversion of the 6049 MHz line requires column densities in excess of $10^{17}\,\mathrm{cm}^{-2}$, while inversion at 4765 MHz (not shown) requires an OH column a few times higher still.

OH (1720 MHz) masers are a signature of SNR – molecular cloud interactions (Frail *et al.* 1994; Wardle & Yusef-Zadeh 2002). Masing at 6049 MHz may take over this role when the OH column density exceeds $10^{17}\,\mathrm{cm}^{-2}$, too high for 1720 MHz masers to exist. Note, however, that the OH column density typically produced in SNR–cloud interactions is uncertain. Existing models of OH production rely on UV or X-ray dissociation of the water produced in molecular shocks, and yield column densities $\lesssim 10^{16}\,\mathrm{cm}^{-2}$ (Lockett

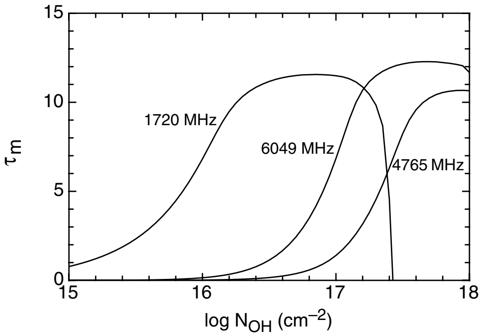

Figure 1. Maser optical depth, τ_m ($I_\nu \propto \exp(\tau_m)$) of the 1720 MHz OH line and its analogues at 6049 and 4765 MHz, as a function of OH column density for T = 50 K and $n_H = 10^5 \mathrm{cm}^{-3}$.

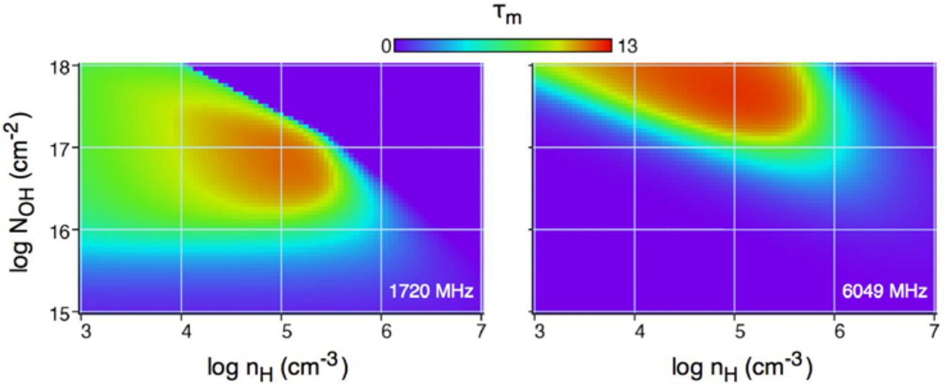

Figure 2. Maser optical depth as a function of n_H and N_{OH} for T = 50 K for the 1720 MHz (left) and 6049 MHz (right) lines of OH.

et al. 1999; Wardle 1999). As the dissociation rate of OH is approximately half that of H_2O, these models predict OH/$H_2O \lesssim 2$, and typically much less. This conflicts with recent absorption measurements in IC 443, which find that $N_{H_2O} \sim 10^{14-15} \mathrm{cm}^{-2}$ (Snell *et al.* 2005) and $N_{OH} \sim 10^{16-17} \mathrm{cm}^{-2}$ (Hewitt *et al.* 2006). Preliminary analysis of a survey for 6049 MHz masers towards southern SNRs has not yielded detections to date (see McDonnell, Vaughan & Wardle, elsewhere in these proceedings).

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