DUSTY MASER SITES
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Introduction

Since the discovery of OH masers nearly 35 years ago, evidence has accumulated linking OH and H$_2$O masers to massive young stars and ultra-compact HII regions (UCHII). Most pumping models rely on a young stellar object (YSO) to provide the excitation energy for maser action. However, the nature of the objects powering interstellar masers (for example, their mass and evolutionary stage) is not known.

For masers associated with HII regions the presence of a massive star (M > 20M$_\odot$) in the ZAMS or later evolutionary stage is certain. However, recent continuum observations at 3cm (8.5 GHz) toward 45 interstellar OH and H$_2$O maser sites show that fewer than half of these sites have UCHII emission at the mJy level (Forster & Caswell, 1999a). This result is difficult to reconcile with the idea that all maser sites contain embedded OB-type stars. So - what is providing the pump energy necessary for maser action?

One possibility is that these sites are still in a contraction phase and have not yet produced stars hot enough to create an HII region. In this case the energy for maser excitation might be provided by protostellar accretion shocks (Forster & Caswell, 1999a). Another possibility is that OB stars are there, but heavy absorption of stellar UV by dust near the photosphere (Wood & Churchwell, 1989), or rapid accretion of neutral material (Walmsley, 1995), has stalled the development of an HII region. It is also possible that lower-mass stars of spectral type B1 or later, which are too cool to produce an HII region, provide the maser pump energy.

In order to study the YSOs responsible for powering galactic maser sites we have made observations in the continuum and molecular lines toward twelve fields containing both OH and H$_2$O masers using the BIMA interferometer. Continuum observations at 1cm (30 GHz), 3mm (90 GHz) and 1mm (220 GHz) were obtained using scaled arrays to provide an angular resolution of ~7" at all frequencies. Simultaneous spectral line observations were obtained in HCN, HCO$^+$ and $^{13}$CS at 3mm, and in several transitions of H$_2$CO, HC$_3$N and CH$_3$OH at 1mm.

The spectral index of free-free radiation from an optically thin HII region is $\alpha = -0.1$ ($S \propto \nu^\alpha$). For optically thick dust $\alpha = 2.0$, reaching 4.0 in the optically thin limit. All twelve fields have been observed at both 3mm and 1cm with BIMA, and most have also been observed at 3cm with the Australia Telescope. At cm wavelengths the contribution from warm dust is small, and the radiation is essentially all from ionized hydrogen. At 3mm both HII emission and thermal dust emission can be important. Thus the dust distribution can be derived from the 3mm images by removing the HII distribution obtained at cm wavelengths.

Fig 1 - The Maser Sites

The twelve fields observed were chosen from the Forster & Caswell (1999b) list of galactic interstellar maser sites containing both OH and H$_2$O masers. Most fields contain several maser sites with separations larger than ~7". BIMA 3mm continuum images are shown here for each field, with the masers indicated by symbols. In all cases except 359.14+0.03 significant continuum emission was detected at 3mm. In most cases the emission is coincident with or adjacent to a maser site.
Fig 2 - Dust and Molecules

1cm continuum images are shown here for four fields, two of which contain significant HII emission and two which do not. The dust distribution, obtained by subtracting the 1cm images from the 3cm images, is shown in the second column. The third column shows the distribution of molecules for selected spectral lines observed at 3mm.

The difference between the continuum distributions at 1cm and 3mm shows clearly enhanced 3mm emission at the maser sites, indicating the presence of substantial amounts of dust. Molecular emission from HCN, HCO$^+$ and $^{13}$CS is also found to be strongly clumped near the masers. These observations indicate that the masers are located in warm, dense molecular cores, reinforcing the idea that OH and H$_2$O masers are signposts of massive star formation.

Maser Sites - HII, Dust and Molecules

Fig 3 - Dust Mass and Opacity

BIMA observations at 1mm of two fields without HII regions reveal strong continuum emission. 1cm, 3mm and 1mm images are shown, along with the measured peak fluxes from 3cm to 1mm $\lambda$, for both fields. The spectral indices between 3mm and 1mm are 2.9 and 2.5 for 23.44-0.18 and 12.91-0.26 respectively, confirming the presence of warm dust. Assuming optically thin dust at a temperature of 100 K and an emissivity law $\beta = 1$, the dust masses derived from the 1mm flux densities are 53 M$_{\odot}$ and 111 M$_{\odot}$. These are lower limits since the dust is not completely optically thin.

Summary and Conclusions

Multi-wavelength continuum and spectral line observations toward twelve OH/H$_2$O maser sites show that the masers are embedded in dusty, warm molecular cores with masses of order 100 M$_{\odot}$. These results support the long-held belief that OH/H$_2$O masers mark sites of massive star-formation. However, the absence of an HII region at about half of the sites indicates either that formation of a substantial ionized zone around a massive star has been retarded somehow, or that OB-type stars have not formed in these cores.

Possibilities considered to account for the low cm $\lambda$ continuum levels measured toward maser sites are: excitation by lower mass stars (later than B1); quenching of ionization by dust or high infall rates; and a protostellar evolutionary stage for the embedded YSO. High resolution observations at sub-millimeter and far-infrared wavelengths would be of great value in distinguishing among these possibilities.

References