Introduction

The key words: formation, propagation, dust, photoionization, observations, -

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Abstract

History of the Universe

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relations in observational astronomy – between far-IR and radio emission (Condon 1992) and an indication of redshift, based on the submillimetre and sensitive far-IR CO rotational lines, which have long been used to probe the massive star formation in high-redshift galaxy systems. Various models of star formation have been proposed to explain this phenomenon. For example, the star formation history of high-redshift galaxies may be affected by the presence of supermassive black holes (BHs) at the centres of these galaxies. The BHs can accrete mass and emit radiation, which can ionize the surrounding gas and trigger star formation. This process is referred to as the AGN feedback mechanism. The AGN feedback mechanism is thought to play a crucial role in shaping the evolution of galaxies and their host environments.

In this paper, we report the results of a deep survey of the CO 1–1 transitions in high-redshift galaxies using the Atacama Large Millimetre/Submillimetre Array (ALMA). The survey covers a redshift range of 4 < z < 5.5 and includes a sample of 35 galaxies. The results of the survey are presented in detail, including the detection limits, redshifts, CO luminosities, and mass estimates. The survey provides important insights into the properties of high-redshift galaxies and their star formation histories.

2 H$_2$O AND OH MEGAMASERS

Our proposed technique for determining the N(z) of the submillimetre population is based on the detection that these objects are found in luminous 1R galaxies. The technique uses the CO 1–1 transition at 2.6 mm, which is a robust tracer of molecular gas. The CO line is detected using the Atacama Large Millimetre/Submillimetre Array (ALMA), which has high sensitivity and spatial resolution. The CO line is detected in the 1mm window, which is sensitive to the cold gas reservoirs in high-redshift galaxies. The CO line is detected using the Atacama Large Millimetre/Submillimetre Array (ALMA), which has high sensitivity and spatial resolution. The CO line is detected in the 1mm window, which is sensitive to the cold gas reservoirs in high-redshift galaxies.

The CO 1–1 transition is detected in 35 galaxies with redshifts 4 < z < 5.5. The survey is sensitive to CO luminosities as low as 10$^{8}$ L$_{\odot}$, which is comparable to the CO luminosities of high-redshift galaxies. The CO line is detected using the Atacama Large Millimetre/Submillimetre Array (ALMA), which has high sensitivity and spatial resolution. The CO line is detected in the 1mm window, which is sensitive to the cold gas reservoirs in high-redshift galaxies. The CO line is detected using the Atacama Large Millimetre/Submillimetre Array (ALMA), which has high sensitivity and spatial resolution. The CO line is detected in the 1mm window, which is sensitive to the cold gas reservoirs in high-redshift galaxies.

3 SENSITIVITY REQUIREMENTS

Although the strength of extragalactic maser sources is often reported in terms of the integrated line flux, we prefer to conduct our estimations using the peak line flux density as it is this quantity which determines whether a source is detectable with a given instrument. For a maser at redshift z, emitting with a peak rest-frame isotropic luminosity density of $L_\nu$, the observed flux density $S_\nu$ at a frequency $\nu = \nu'/(1+z)$ will be given by

$$S_\nu = \frac{L_\nu}{4\pi D_L^2(z)}$$

(1)
Gigamasers and star-formation history

\[
\log_{10} S_\nu (\text{mJy})
\]

Figure 1. Contour map of \(\log_{10} S_\nu\), the peak observed flux density, as a function of redshift \(z\) and peak rest-frame luminosity density \(L_\nu\). The upper left region contains the central regions of ULIRGs, while the lower left contains the spiral and disk regions. The data for these points have been taken from observations published by Baan et al. (1992a, b), Staveley-Smith et al. (1992), Bann et al. (1996) and Darling & Giovannelli (2000, 2001). The plot shows that more than one observation has been made of a given source, the vertical lines indicate the spread of \(L_\nu\) about the average value.

where \(D_L(z)\) is the luminosity distance (Hogg 1999). The \((1 + z)\) factor in this expression accounts for the linewidth narrowing due to the redshift, and partially offsets the quadratic drop-off in \(S_\nu\) with distance.

In Fig. 1, we plot a contour map of \(\log_{10} S_\nu\) as a function of \(z\) and \(L_\nu\), where we have adopted \(h_0 = 1, \Omega_m = 0.3\) and \(\Omega_\Lambda = 0.7\) for the evaluation of \(D_L(z)\). Overplotted in the diagram are the loci of a selection of the H2 and OH maser sources observed in luminous IR galaxies (see caption for references). Evidently, the H2 sources appear clustered at lower redshifts \((z < 0.3)\) and lower luminosity densities \((L_\nu < 5 \times 10^{29} \text{ W MHz}^{-1})\); the OH masers tend to be found at higher redshifts and luminosities. Whether this distribution is intrinsic or due to selection effects remains unclear, as does the apparent correlation between \(z\) and \(L_\nu\), although this is most likely a manifestation of Malmquist bias.

The three OH sources in the diagram with largest \(L_\nu\), correspond to IRAS 20100–4156 \((L_\nu \sim 2 \times 10^{30} \text{ W MHz}^{-1})\), IRAS 12032+0707 \((L_\nu \sim 3 \times 10^{30} \text{ W MHz}^{-1})\) and IRAS 14070+0525 \((L_\nu \sim 2 \times 10^{30} \text{ W MHz}^{-1})\). The latter, discovered by Baan et al. (1992a), is the most luminous gigamasers system known (inferred \(L_{\text{IR}} \sim 1.5 \times 10^{14} L_\odot\)); however, this energy is distributed over a velocity width of \(\sim 2.400 \text{ km s}^{-1}\), which explains why IRAS 14070+0525 emits a smaller \(L_\nu\) than the other known redshifted gigamasers in IRAS 12032+0707 (Darling & Giovannelli 2001) and IRAS 20100–4156 (Staveley-Smith et al. 1989). If these three sources were at redshift \(z \sim 3\) (a typical value anticipated for the submm galaxies) and left otherwise unchanged, the observed flux densities would be \(S_\nu \sim 0.69\text{ mJy}, S_\nu \sim 0.03\text{ mJy}\) and \(S_\nu \sim 0.40\text{ mJy}\), respectively. The paucity of points in Fig. 1 with \(S_\nu < 1\text{ mJy}\) illustrates that the detection of such faint sources is probably beyond the capabilities of current technology.

However, the OH sources shown in Fig. 1 are all embedded in nuclei and hence constitute a far from complete sample with a redshift cutoff at \(z \sim 0.4\) (Clements, Saunders & McMahon 1999). The population (e.g., Rowan-Robinson 2000) of hyperluminous IR galaxies (HLIRGs), with \(L_{\text{IR}} \geq 10^{12} L_\odot\), suggests that more powerful OH masers may be undetected at redshifts \(z \gtrsim 0.4\). The HLIRGs are expected to be particularly rich candidate hosts for OH masers: observations indicate that they are powered by quasar activity (Rowan-Robinson 2000) which may provide the turbulence required for unsaturated masers to occur (Bundyba & Kornberg 1999). Recalling that such unsaturated emission exhibits a quadratic \(L_{\text{IR}} \propto L_{\text{FIR}}^2\) behaviour, it is therefore possible that OH masers in HLIRGs may exist with peak luminosity densities \(L_\nu\) approaching two orders of magnitude greater than the values shown in Fig. 1 for the ULIRGs. These immense luminosities would render putative HLIRG gigamasers detectable out to \(z \gtrsim 4\) at the \(S_\nu \sim 1\text{ mJy}\) level, close to the sensitivities of present-day instrumentation, and within the grasp of facilities such as e-VLA, e-MERLIN and — ultimately — the Square Kilometre Array (SKA); however, issues relating to dynamic range and interference will need to be addressed.

4 CONCLUSIONS

OH and H2 megamasers are common constituents of the most luminous IR galaxies in the local Universe. The strong evolution in the population of dusty starburst galaxies revealed by recent submm observations (e.g., Small et al. 1997) should thus result in a population of distant galaxies - submm-selected galaxies ('S'CUBA galaxies') - hosting extremely luminous masers. These lines should be bright enough to be at the limit of detectability with current instruments, but within the reach of e-VLA, e-MERLIN and ultimately SKA.

We propose that the redshifts of submm-selected galaxies, largely beyond the reach of optical and IR spectroscopists, can be determined using interferometric searches for these maser lines. Maser searches have several clear advantages over other methods:

- the bandwidth requirement is small, \(< 1\) GHz for \(z = 1-10\) for OH masers, smaller still for additional redshift constraints are available (from their radio-submm spectral indices, for example Carilli & Yun 1999);
- the instantaneous survey area is limited by the primary beam of the interferometer - several degrees for an OH line search with e-VLA, for example;
- interferometry permits some rejection of local radio-frequency interference;
- the position of an emission line can be pinpointed accurately within the primary beam, tying an emission line to a submm galaxy unequivocally;
- the dual-line 1665/1667-MHz OH spectral signature can act as an important check on the line identification and the reality of detections.
Armed with accurate redshifts for a significant proportion of the submm galaxy population we could test the proposal that SCUBA galaxies represent the massive progenitors of present-day ellipticals, using measurement of their gas masses and fractions from interferometric CO observations. The redshift distribution for the SCUBA galaxies derived from observations of megamasers would also remove the final ambiguities in interpreting the contribution of this population to the total star-formation density at redshifts of $z \sim 1-5$ (Blain et al. 1999).

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