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Gigamasers: the key to the dust-obscured star formation history of the Universe?

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ABSTRACT

We discuss the possibility of using OH and H_2O gigamasers to trace the redshift distribution of luminous, dust-obscured, star-forming galaxies. It has long been thought that ultraluminous, interacting galaxies should host gigamasers, owing to their vast pumping infrared (IR) luminosity, the large column density of molecules available to populate the maser states and the turbulent motion of the gas in these dynamically complex systems, which allows unsaturated maser emission. OH masers may thus be well suited to the redshift-blind detection of ultraluminous and hyperluminous infrared galaxies ($L_{\rm FIR} \geq 10^{12}\,{\rm L}_{\odot}$) such as those uncovered by the SCUBA submillimetre camera. The bandwidth requirement is low, <1 GHz for $z = 1-10$ (lower still if additional redshift constraints are available) and the dual-line 1665-/1667-MHz OH spectral signature can act as a check on the reality of detections.

Key words: galaxies: formation – galaxies: starburst – cosmology: observations – early Universe.

1 INTRODUCTION

The discovery of a distant population of luminous submillimetre (submm) galaxies has revolutionized our understanding of galaxy formation and evolution (Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999; Carilli et al. 2000). Debate continues regarding the relative importance of obscured and unobscured star formation, the fraction of active galactic nuclei (AGN) in the submm galaxy population and the relationship, if any, between Lyman-break galaxies and submm galaxies (Adelberger & Steidel 2000; Chapman et al. 2000; Eales et al. 2000; Peacock et al. 2000; Smail et al. 2001); nevertheless, it is clear that rest-frame far-infrared (far-IR) energy that has been reprocessed by dust and redshifted into the waveband accessible to SCUBA (Holland et al. 1999) traces a galaxy population that makes a significant, and possibly dominant, contribution to the star formation density at $z > 1$.

It was realized from the outset that the most crucial piece of information required to derive the history of obscured star formation from the submm population is its redshift distribution, $N(z)$ (Blain et al. 1999). Knowledge of $N(z)$ breaks degeneracies in the models and allows the nature of the galaxies to be explored, most importantly providing estimates of their masses via observations of CO. Initial efforts to target the first few SCUBA galaxies were very successful, resulting in four redshifts from a sample of fifteen weakly lensed galaxies in the Smail et al. (1998) sample (Ivison et al. 1998; Soucail et al. 1999; Ivison et al. 2000; Frayer et al., in preparation); three of these have so far been confirmed as massive and gas-rich systems through CO line mapping (Frayer et al. 1998, 1999; Kneib et al., in preparation).

However, the realization that the majority of the submm population have no plausible optical counterparts ($I > 26$, e.g. Smail et al. 2000) has meant that the possibility of a complete optical spectroscopic survey has had to be dismissed (e.g. Barger et al. 1999). Even in the IR, only around half of the galaxies are identified by $K < 22$, often as extremely red objects (EROs, $I - K > 5$: Smail et al. 1999; Gear et al. 2000; Ivison et al. 2000), giving little hope to IR spectroscopists either.

As in other branches of extragalactic research, attention has therefore been diverted to broadband photometric redshift techniques. Unfortunately, the classical analysis of optical/IR photometry has been shown to be misleading for even the few visible examples of these very dusty galaxies, owing to the complex effects of dust on the optical spectral energy distribution, a problem that is further compounded by the low photometric precision available for these faint galaxies. However, Carilli & Yun (1999) made a significant breakthrough with the realization that one of the strongest correlations in observational astronomy – between far-IR

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and radio emission (Condon 1992) – could be exploited to give an indication of redshift, based on the submm fluxes and sensitive radio detections of the galaxies. Several variants of this technique have been developed (Carilli & Yun 2000; Barger, Cowie & Richards 2000; Dunne et al. 2000), although, based on comparison against the few submm galaxies with known redshifts, none is demonstrably better than the original. The technique has been used to demonstrate convincingly that the median redshift of submm galaxies must be in the range $2 < z < 3.5$, with no significant low-redshift tail (Smail et al. 2000; cf. Smail et al. 1998; Lilly et al. 1999).

How else can progress be made towards the determination of the $N(z)$ for the submm population? Some have proposed that searches for CO rotational lines centred on submm galaxy positions are the way forward (e.g. Blain 2000; Hughes 2000). The CO lines are certainly expected to be luminous, but the bandwidth requirements (~ 100 GHz) of such an approach are several orders of magnitude beyond the capabilities of current instrumentation. Moreover, prior to the advent of ALMA (Brown 1999), observers will be reliant on current/planned 10–50 m mm/submm single-dish facilities. As it has long been known that even *interferometric* detections of CO (where one benefits from stable baselines) in galaxies with *known* redshifts are extraordinarily difficult (Frayer et al. 1998), there are obviously substantial technical difficulties to overcome when undertaking redshift-blind, single-dish CO searches. It is clear therefore that we should explore other avenues to measure the redshifts of the submm galaxy population and so understand more about their detailed properties.

In this paper we propose an alternative method for determining the redshifts of submm galaxies, based on the expectation that these dusty, ultraluminous galaxies will exhibit similar behaviour of their H_2O and OH maser activity to that observed in luminous IR galaxies in the local Universe. We first discuss the background to this proposal (Section 2), based on the properties of H_2O and OH masers in the local Universe, before investigating, in Section 3, the feasibility of these observations using current and future instrumentation. Finally, in Section 4, we state the main conclusions of this study.

2 H$_2$O AND OH MEGAMASERS

Our proposed technique for determining the $N(z)$ of the submm population is based on the expectation that luminous submm galaxies (typically $\sim 10^{12} h_{65}^{-2}\,L_\odot$, where $h_{65} \equiv H_0/65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) exhibit similar scaling of their H_2O and OH maser activity to that observed in luminous IR galaxies in the local Universe. Observations of OH emission in local luminous IR galaxies, primarily owing to the 1665-/1667-MHz ground rotational state transitions, indicate a strong $L_{OH} \propto L_{FIR}^2$ correlation between (isotropic) maser and far-IR luminosities (e.g. Baan 1989). This relationship has been explained in terms of a model first proposed by Baan (1985), whereby an OH population inversion, efficiently pumped by the far-IR flux, provides unsaturated amplification of the background radio continuum; the Condon (1992) far-IR/radio luminosity correlation then leads to the observed quadratic dependence of L_{OH} on L_{FIR}. More recent work by Kandalian (1996) has claimed that the correlation is merely a consequence of Malmquist bias, the true relationship being closer to $L_{OH} \propto L_{FIR}^{1.38}$, which Diamond et al. (1999) have proposed to result from the admixture of unsaturated and saturated emission.

Regardless of the precise character of any L_{OH}/L_{FIR} relationship, however, it is clear (e.g. Baan 1989; Baan, Haschick & Henken 1992b; Briggs 1998; Darling & Giovanelli 2000) that powerful OH massing is relatively common within the ultraluminous IR galaxy (ULIRG) population, with upwards of 50 per cent of those galaxies with $L_{FIR} \gtrsim 10^{11-12}\,L_\odot$ supporting megamasers ($L_{OH} \gtrsim 10\,L_\odot$) or gigamasers ($L_{OH} \gtrsim 10^3\,L_\odot$). Based on the assumption that the luminous submm galaxies are the high-redshift counterparts of ULIRGs (Smail et al. 2001), it is therefore quite reasonable to expect strong OH maser emission from a large proportion of the submm population, which, if detectable, will allow the accurate determination of their $N(z)$.

Although 22.235-GHz H_2O megamasers show somewhat different characteristics from the OH maser systems (e.g. Braatz, Wilson & Henkel 1994, 1996), similar arguments may be deployed in favour of their potential as redshift markers for luminous submm galaxies. H_2O masers are more typically associated with AGN and are less useful tracers of star formation than their OH counterparts, but a significant number of submm galaxies are known to harbour active nuclei (Ivison et al. 1998, 2000; Frayer et al., in preparation). If detected, high-resolution studies may yield information on their black hole masses (Miyoshi et al. 1997), in addition to their redshifts. The bandwidth requirement for detection of H_2O masers is only ~ 9 GHz ($\nu_{obs} = 2$–11 GHz for $z = 1$–10), similar to the bandwidth planned for the new Very Large Array (VLA) correlator. In the case of OH masers this requirement drops below 1 GHz ($\nu_{obs} = 165$–835 MHz for $z = 1$–10). As there is no significant submm galaxy population at $z < 1$ (Smail et al. 2000), the technique avoids contamination by H I emission from local galaxies (Briggs 1998) and we can thus search a relatively clean part of the electromagnetic spectrum using existing interferometers with superb instrumentation, high aperture efficiencies and large collecting areas [e.g. VLA, Westerbork Synthesis Radio Telescope (WSRT), Australia Telescope Compact Array (ATCA)].

Inevitably, the difficulties with this new technique will lie in its stringent sensitivity and dynamic-range requirements, as well as radio-frequency interference in the 165–835 MHz (UHF) band (see e.g. `http://www.atnf.csiro.au/SKA/intmit`). In the following section, we estimate the sensitivity requirements by extrapolating from previous observations of H_2O/OH megamasers and gigamasers in luminous IR 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 that 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_ν at a frequency $\nu \equiv \nu'/(1+z)$ will be given by

$$S_\nu = (1+z)\frac{L_{\nu'}}{4\pi D_L^2(z)}, \tag{1}$$

where $D_L(z)$ is the luminosity distance (Hogg 1999). The $(1+z)$ factor in this expression accounts for the linewidth narrowing as a result of the redshift, and partially offsets the quadratic drop-off in S_ν 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 $h_{65} = 1$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ for the evaluation of $D_L(z)$. Overplotted in the diagram are the loci of a selection of the H_2O and OH maser sources observed in luminous

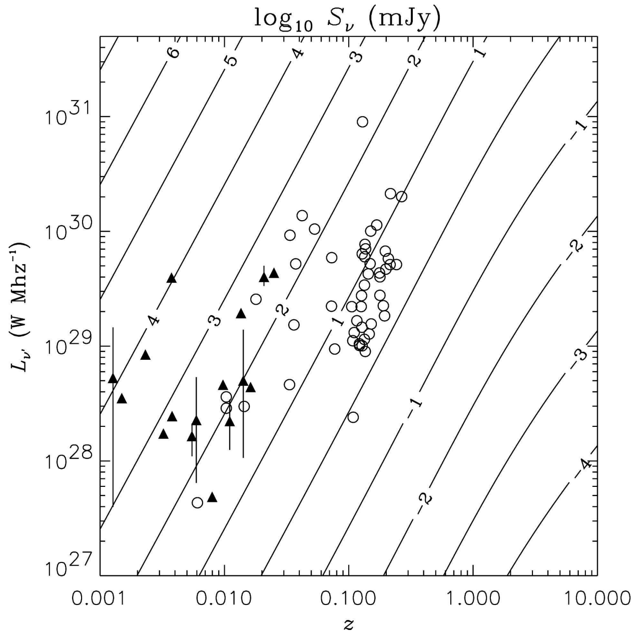

Figure 1. Contour map of $\log_{10} S_\nu$, the peak observed flux density, as a function of redshift, z, and peak rest-frame luminosity density, $L_{\nu'}$. Also shown are observations of H_2O (filled triangles) and OH (open squares) maser sources in luminous IR galaxies; the data for these points have been calculated from observations published by Baan et al. (1992a,b), Stavely-Smith et al. (1992), Braatz et al. (1996) and Darling & Giovanelli (2000, 2001). Where more than one observation has been made of a given source, the vertical lines indicate the spread of $L_{\nu'}$ about its average value.

IR galaxies (see caption for references). Evidently, the H_2O sources appear clustered at lower redshifts ($z \lesssim 0.3$) and lower luminosity densities ($L_{\nu'} \lesssim 5 \times 10^{29}\,\mathrm{W\,MHz^{-1}}$); the OH masers tend to be found at higher redshifts and luminosities. Whether this distribution is intrinsic or a result of 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 $20100 - 4156$ ($L_{\nu'} \sim 9.0 \times 10^{30}\,\mathrm{W\,MHz^{-1}}$), IRAS $12032 + 0707$ ($L_{\nu'} \sim 2.1 \times 10^{30}\,\mathrm{W\,MHz^{-1}}$) and IRAS $14070 + 0525$ ($L_{\nu'} \sim 2.0 \times 10^{30}\,\mathrm{W\,MHz^{-1}}$). The latter, discovered by Baan et al. (1992a), is the most luminous gigamaser system currently known (inferred $L_{\mathrm{OH}} \sim 1.05 \times 10^4\,\mathrm{L_\odot}$); however, this energy is distributed over a velocity width of $\sim 2400\,\mathrm{km\,s^{-1}}$, which explains why IRAS $14070 + 0525$ exhibits a smaller $L_{\nu'}$ than the less luminous yet narrower-lined gigamasers in IRAS $12032 + 0707$ (Darling & Giovanelli 2001) and IRAS $20100 - 4156$ (Stavely-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 $S_\nu \sim 0.089$ mJy, $S_\nu \sim 0.093$ mJy and $S_\nu \sim 0.40$ mJy, respectively. The paucity of points in Fig. 1 with $S_\nu < 1$ 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 *IRAS*-selected ULIRGs, and hence constitute a far-IR flux-limited sample, with a redshift cut-off at $z \sim 0.4$ (Clements, Saunders & McMahon 1999). The population (e.g. Rowan-Robinson 2000) of hyperluminous IR galaxies (HLIRGs), with $L_{\mathrm{FIR}} \gtrsim 10^{13} h_{65}^{-2}\,\mathrm{L_\odot}$, suggests that more powerful OH masers may lie undetected at redshifts $z \gtrsim 0.4$. The HLIRGs are especially promising candidate hosts for OH massing: observations indicate that they are powered by starburst activity (Rowan-Robinson 2000), which may provide the turbulence required for unsaturated massing to occur (Burdyuzha & Komberg 1990). Recalling that such unsaturated emission exhibits a quadratic $L_{\mathrm{OH}} \propto L_{\mathrm{FIR}}^2$ 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 $S_\nu \sim 1$ 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 H_2O 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. Smail et al. 1997) should thus result in a population of distant galaxies – submm-selected galaxies ('SCUBA 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:

(i) The bandwidth requirement is small, <1 GHz for $z = 1-10$ for OH masers, smaller still if additional redshift constraints are available (from their radio–submm spectral indices, for example Carilli & Yun 1999).

(ii) 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.

(iii) Interferometry permits some rejection of local radio-frequency interference.

(iv) The position of an emission line can be pinpointed accurately within the primary beam, tying an emission line to a submm galaxy unequivocally.

(v) 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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