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OH megamasers as extragalactic diagnostics

Ylva M. Pihlström

Department of Physics and Astronomy, 800 Yale Blvd. NE, 1 University of New Mexico, Albuquerque, NM 87131, USA
email: ylva@unm.edu

Abstract. Luminous, extragalactic OH masers are excellent tracers of merger triggered, intense star formation in Ultra Luminous Infrared Galaxies (ULIRGs). As such, they are tracers of high density regions in the centers of active galaxies. From high resolution imaging of the 1667 MHz emission in a small sample of OH megamaser galaxies, the general consensus is that most of the maser emission arises in thick, circumnuclear structures. Here we summarize the current work on OH megamasers, and present the preliminary results on VLA observations of the 1720 MHz satellite line in III Zw 35, Mrk 231 and Arp 220. We also briefly mention ongoing work on investigating the nature of the high molecular gas density environment in a sample of ULIRGs, using CO (J=3–2) observations. A subset of the ULIRG sample harbors OH megamaser emission, and is therefore suited for comparing gas properties between ULIRGs with and without OH megamaser emission.

Keywords. masers, galaxies:starburst, radio lines: galaxies, instrumentation: high angular resolution

1. Introduction

The extremely luminous 1667 MHz OH maser emission detected in extragalactic sources has been shown to be associated with the most central regions of Ultraluminous Infrared Galaxies (ULIRGs). ULIRGs are known to be merging systems (e.g. Clements *et al.* 1996), and as a result they display very high far-infrared (FIR) to optical ratios and $L_{FIR} > 10^{11}$ $L_{\odot}$. ULIRGs can be linked to a number of fundamental research areas like the formation of elliptical galaxies, the formation of quasars and the high-z proto-galaxies detected by SCUBA and MAMBO. For instance, studies of ULIRGs allow investigation of the possible evolutionary relationship between Active Galactic Nuclei (AGN) and ULIRGs (the starburst-AGN connection), since both AGN and starburst activity are suggested to be the result of mergers. Other examples of specific research topics include galaxy evolution scenarios, and how star formation and AGN activity might affect the host galaxy and the intergalactic medium.

Given that the OH megamasers reside in merging systems, they could serve as tracers of merger activity. Ultimately, the detection of OH megamasers over a wide range of redshifts could help estimating the merger rate across the cosmic time (Darling & Giovanelli 2002b). Several authors suggest the plausibility of detecting bright OH megamasers at high redshifts (Briggs 1998), and even 'gigamasers' back to the epoch of re-ionization (Darling & Giovanelli 2002b). A future deep OH megamaser survey could perhaps distinguish between different galaxy evolution models. Darling & Giovanelli (2002b) note that even a non-detection could be useful, since maybe then our current assumption that the ULIRGs are the local versions of the high-z submillimeter sources should be re-examined. By these examples it is clear that the OH megamaser emission could serve as an important extragalactic diagnostic tool. Darling (these proceedings) presents a more detailed review of OH megamasers and their properties. Here we will summarize the

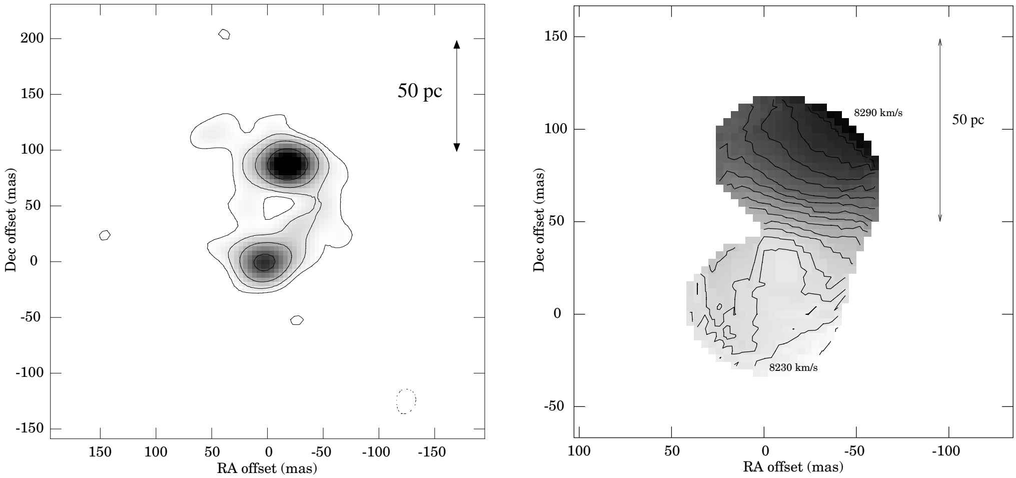

Figure 1. Results from EVN and MERLIN observations of the 1667 MHz OH maser emission in III Zw 35. *a)* Contour map of the integrated maser emission. The beam size is 33 × 29 mas, and plotted contours are -1, 1, 2, 4 and 8 times the 3σ rms noise of 2.7 mJy/beam. *b)* The corresponding velocity field. The gray-scale is between 8224 and 8300 km s^{-1}. Contours are from 8230 km s^{-1} and increasing by 5 km s^{-1} up to 8290 km s^{-1}. The beam size is 43 × 36 mas; at this resolution the weaker Eastern side is blanked out due to low SNR.

current understanding of the OH megamasers derived mostly from observations of the 1667 MHz main line (Sect. 2). Thereafter we present preliminary results of observations of the much weaker 1720 MHz satellite line in a few of these systems (Sect. 3). Finally, in Sect. 4 we briefly discuss ongoing work on submillimeter data of a sample of ULIRGs, with the aim of investigating any differences in the physical properties or distribution of dense gas in ULIRGs with and without OH megamaser emission.

2. The OH 1667 MHz line

The best observationally studied OH transition is the 1667 MHz main line, which is usually stronger than the 1665 MHz main line with a value often reasonably well in agreement with the expected 9:5 ratio assuming thermodynamic equilibrium. Single dish spectra display line widths ranging from 10 to 1000 km s^{-1}, often with multiple peaks. The emission is generally unresolved at VLA angular scales ($\sim 1.4''$), but can be resolved using long baseline arrays such as the VLBA, EVN and MERLIN. Hitherto a handful of sources have been mapped at high resolution in the 1667 MHz line, and in all cases the emission is centered at one (or both) of the merger system nuclei. Including information from the velocity distribution, there is an emerging general picture of the OH megamasers, with the bulk of the emission being diffuse and distributed in $\sim$ 100 parsec scale circumnuclear structures. Typical enclosed masses are of the order of 10^7 $M_\odot$. Examples include III Zw 35 (Pihlström *et al.* 2001, see Fig. 1), Mrk 231 (Richards *et al.* 2005, Klöckner, Baan & Garrett 2003), Mrk 273 (Yates *et al.* 2000) and the eastern nucleus of Arp 220 (Rovilos *et al.* 2003).

To this general picture of the OH megamasers, however, we have to add the presence of extremely compact sources. At the highest angular resolution, the 1667 MHz emission is most often resolved, and in some sources (e.g. III Zw 35 and Arp 220; Diamond *et al.* 1999, Lonsdale *et al.* 1998) part of the emission is confined to very compact (< 1 pc) scales. More interestingly, the spectra still display line widths exceeding several tens of

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$\mathrm{km\,s^{-1}}$, possibly indicating high turbulence. Recent amplification modelling have invoked a clumpy OH medium in order to explain the observed maser characteristics (Parra *et al.* 2005). This model shows that compact masers might be the result of lines of sights intersecting several smaller clouds, with resulting maser emission characteristics very different from what is expected in the case of a smooth medium. Other explanations for the compact emission are also likely, in particular very high sensitivity observation of the OH lines in Arp 220 strongly suggest a connection of the compact masers with individual radio supernovae (Lonsdale, these proceedings).

3. The 1720 MHz line

Assuming thermodynamic equilibrium, the expected line ratio of the 1667 and 1720 MHz transitions is 9, thus a much weaker 1720 MHz line. As a consequence, extragalactic 1720 MHz OH has not been studied in detail, and we have little information about this emission. After a few 1720 MHz detections in early searches for emission in both the main and satellite lines (1612, 1665, 1667 and 1720 MHz) of OH in extragalactic sources (e.g. Baan, Haschick & Henkel 1992), subsequent surveys concentrated on finding the brighter 1667 and 1665 MHz lines using a more limited bandwidth. Examples of sources with 1720 MHz emission include Mrk 231, Arp 220, III Zw 35 and IRAS 17208-0014 (Baan, Haschick & Henkel 1989, Baan & Haschick 1987, Baan, Haschick & Henkel 1992, Martin *et al.* 1989). The peak flux densities of the 1720 MHz lines are typically a few mJy, with 1667/1720 MHz line ratios in the single dish detections that span from about 20 to 100. Similar to the 1667 MHz lines, the 1720 MHz lines are wide. The velocities are comparable, but not always fully corresponding to the 1667 MHz line velocities.

Due to their weak flux densities, no high angular resolution studies have been performed and little is known about the origin and position of these masers. In recent modelling of OH megamaser pumping by Lockett & Elitzur (2007), a weaker 1720 MHz line is predicted to be associated with the 1667 MHz line. If this is the case, a spatial coincidence is expected between the two lines. Another possible origin of the 1720 MHz emission could be in the region of shocks occurring between the merging nuclei in the ULIRG host. Images of H_2 $v = 1-0$ S(1) 2.12μm emission in NGC 6240 and Arp 220 show that the H_2 emission peaks between the two merging nuclei (van der Werf 1993, van der Werf 1999, van der Werf *et al.* 2000). The authors point out that this spatial position, offset from the starbursting nuclei, argues against stellar associated H_2 excitations mechanism such as UV radiation or shocks from supernova remnants. Instead, the excitation mechanism could be due to slow shocks in the dissipating interstellar medium. Such slow shocks could produce similar pumping environments to what is found for Galactic 1720 MHz masers. If this is the case, the extragalactic 1720 MHz emission should be spatially offset from the 1667 MHz emission.

To determine the spatial position of the 1720 MHz emission and thereby constrain its excitation mechanism and origin, we performed a VLA A-array study of the line in three of the sources with published 1720 MHz single dish spectra (III Zw 35, Arp 220 and Mrk 231). The details of the observations will be presented elsewhere, here we report on the preliminary results.

III Zw 35 is a merger with two optical nuclei separated by 9″. The 1667 MHz emission is associated with the northern nucleus in this source, as is also the infrared and radio continuum emission (Chapman *et al.* 1990). In Fig. 2 we plot the VLA 1720 MHz emission in grey scale on top of the radio continuum. The position of the 1720 MHz is coinciding with the 1667 MHz, in agreement with a starburst origin for the 1720 MHz emission. Within the errors, we recover all flux from the single dish spectra (Fig. 3).

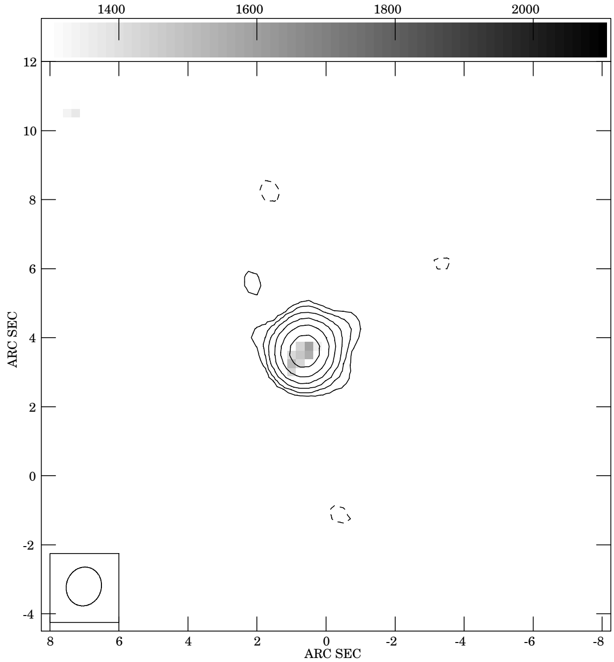

Figure 2. Results from VLA observations of the 1720 MHz OH maser emission in III Zw 35. The contours represents the 1.6 GHz continuum emission, and the plotted contours are −1, 1, 2, 4, 8, 16 and 32 times the 3σ rms noise of 0.7 mJy/beam. The grey scale shows the position of the 1720 MHz maser emission, with the grey scale ranging between 1.3 and 2.1 mJy beam^{-1}.

Mrk 231 displays a similar behavior, with the 1720 MHz emission overlapping with the 1667 MHz. Finally, in Arp 220 the 1720 MHz emission appears to be associated with the Eastern nucleus only, perhaps indicating different density conditions between the two nuclei (1667 MHz emission is present in both of the nuclei of Arp 220).

In summary, extragalactic 1720 MHz OH masers are clearly associated with the starburst regions in mergers. Moreover, 1667/1720 MHz line ratios appear to follow the predictions by the new pumping models of OH megamaser (Lockett & Elitzur 2007).

4. The OH megamaser environment

As mentioned in the introduction, OH megamasers are hosted by ULIRGs. Further, the fraction of OH megamasers in ULIRGs increases with far-infrared luminosity and they are preferentially found in ULIRGs with warm IR color. In general, there is also a higher concentration of dense gas in ULIRGs with higher far-infrared luminosity, for example observed in HCN (Gao & Solomon 2004). Given that molecules form and destroy due to the environment, and that the conditions that are required for OH masers to occur have a limited range, it is likely that the OH megamasers occur during a specific state, or stage of the merger. Thus, to pinpoint the required conditions for OH megamasers, we need to understand the physical connection between galaxy mergers and star formation. In particular, we need a better handle of the time evolution of this process.

A collaboration† has been started with the aim of investigating the dense and warm molecular gas in ULIRGs. The properties and distribution of warm and dense

† The collaboration consists of C. Wilson (McMaster, PI), G. Petitpas, A. Peck, M. Krips (SMA), T.J. Cox (CfA), D. Iono (NAOJ), B. Warren (McMaster), A. Baker (Rutgers), M. Yun

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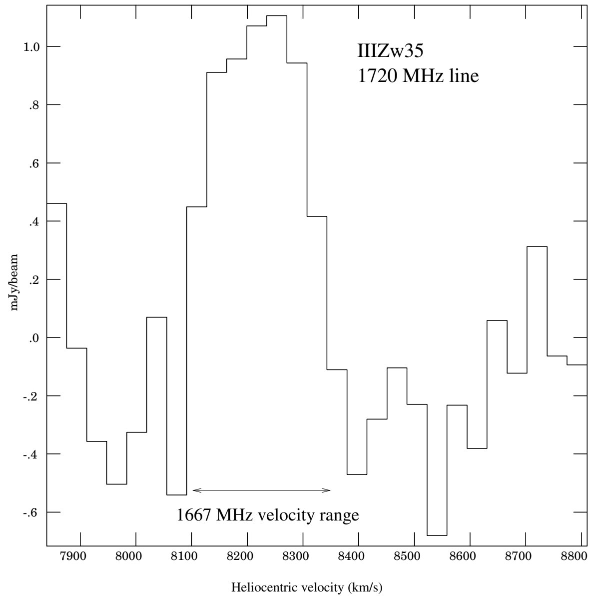

Figure 3. Integrated spectrum of the 1720 MHz OH maser emission in III Zw 35. Within the error bars, all flux is recovered, and the velocity extent of the 1720 and the 1667 MHz lines are in excellent agreement.

molecular gas in ULIRGs could provide key information to understand these processes, since molecular gas is the fuel for star formation. To address this, we selected a sample of 13 ULIRGs, five of which harbors OH megamasers. The sample is observed using the Submillimeter Array (SMA‡), which consists of 6 8m antennas, with a maximum baseline of 500m. SMA has dual frequency operation at 230, 345 and 690 GHz, and with 2 GHz bandwidth we can cover 2600 km s^{-1} at 230 GHz. The five main science goals of the project are as follows:

- To determine the distribution, kinematics and physical conditions of dense molecular gas in ULIRGs
- To determine the spatial distribution of dust in ULIRGs
- To constrain the origin of OH megamasers
- To determine how gas properties might change as the interaction progresses
- To compare properties of dense gas in ULIRGs with high-z submillimeter sources

The first results of this survey are reported on by Wilson *et al.* 2007, and will not be repeated here. However, we note one interesting result that could have important effects on the possibility of high-z submillimeter sources being able to produce 'gigamasers'. Four of the brightest galaxies in the sample were compared to eight high-z submillimeter galaxies that have been mapped in the CO (J=3–2) line. Preliminary results indicate that the molecular gas surface density may be up to an order lower in the high-z sample, than in the local ULIRG sample. This result, however, remain to be confirmed by using our complete sample.

(UMass), Y. Pihlström (UNM), C. Mihos (Case Western Reserve University), S. Matsushita, P. Ho (ASIAA), M. Juvela (Helsinki Observatory) & L. Armus (IPAC)

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5. Conclusions

OH megamasers are tracers of dense star forming regions in (ULIRGs). High resolution imaging of the 1667 MHz emission in a small sample of OH megamaser galaxies yields a general picture where most of the maser emission arises in thick, circumnuclear structures. Velocity gradients of the 1667 MHz OH emission can be used to estimate the enclosed mass in the nuclei of the merging galaxies, and is typically found to be of the order of $\sim 10^7 M_\odot$ within a few 100 parsecs. The large scales over which the relatively diffuse emission is distributed makes these sources less suited for constraining black hole masses (in contrast to the compact, parsec-scale, thin disk emission traced by H_2O megamasers). In addition to the thick torus, a few OH megamaser galaxies also display extremely compact emission that could be the result of amplification in a clumpy, turbulent medium. There are also observations implying that some compact emission is associated with radio supernovae. The 1667 MHz OH main line is the brightest one, and thus the best studied. Preliminary results from VLA observations indicate that the 1720 MHz line emission also is starburst associated, with 1667/1720 MHz line ratios appear close to those predicted by pumping models assuming more or less the same excitation temperatures for the main as well as the satellite lines.

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