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OH megamaser emission in the outflow of the luminous infrared galaxy Zw049.057

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Abstract. High resolution (0.”26 × 0.”13 (70 × 35 pc)) L-band (18 cm) OH megamaser (OHM) e-Merlin observations of the LIRG Zw049.057 show that the emission is emerging from a low velocity outflowing structure - which is foreground to a fast, dense and collimated molecular outflow detected by ALMA. The extremely dusty compact obscured nucleus (CON) of Zw049.057 has no (or only little) OHM emission associated with it - possibly because of too high number densities that quench the OHM. In contrast we detect 6 cm H_2CO emission primarily from the CON-region. We suggest that the OHM-region of Zw049.057 is not directly associated with star formation, but instead occurs in a wide-angle, slow outflow that surrounds the fast and dense outflow. The OHM is pumped by IR emission that likely stems from activities in the nucleus. We briefly discuss how OHM emission can be used as a probe of LIRG-CON galaxies.

Keywords. galaxies: evolution, galaxies: individual: Zw049.057, galaxies: active, galaxies: nuclei, ISM: molecules, ISM: jets and outflows

1. Introduction

Luminous and ultraluminous infrared galaxies (LIRG: $L_{\rm IR} \gtrsim 10^{11}$ L$_\odot$, ULIRG: $L_{\rm IR} \gtrsim 10^{12}$ L$_\odot$) are gas-rich galaxies that harbour intense dust-enshrouded activity in their centres - either in the form of a starburst or an AGN (Active Galactic Nucleus=accreting supermassive black hole). U/LIRGs are often interacting or merging systems and are key phenomena to our understanding of galaxy evolution. They drive powerful molecular outflows (Veilleux *et al.* 2020) that likely act as regulatory processes for star formation and AGN activity. Some U/LIRGs host so called Compact Obscured Nuclei (CONs) with extremely high inferred gas column densities ($N(H_2) > 10^{25}$ cm^{-2}) and dust opacities (e.g. Sakamoto *et al.* 2010; Aalto *et al.* 2015; Falstad *et al.* 2021). The nature of the buried activity in CONs is difficult to discern, but a luminous AGN and/or a starburst with a top-heavy initial mass function (IMF) are possibilities (e.g. Aalto *et al.* 2019). There is mounting evidence that CONs drive collimated dense molecular outflows (Barcos *et al.* 2018; Aalto *et al.* 2020; Yang *et al.* 2023) that are key to our understanding of the nature and growth of the embedded activity. U/LIRGs also often harbour luminous OH megamasers (OHM) (e.g. Mirabel & Sanders 1986) and we are investigating

OHMs as potential probes of CON evolution. Here we present some initial results on the LIRG-CON Zw049.057.

2. The LIRG-CON Zw049.057

Zw049.057 (from now on Zw049) is a nearby (D=56 Mpc (linear scale: ∼270 pc arcsec^{-1} (Katgert *et al.* 1998))). Zw049 is a LIRG with an infrared luminosity of $L_{\rm IR} \sim 1.8 \times 10^{11}$ $L_\odot$ (Sanders *et al.* 2003) It has a highly inclined disk (Scoville *et al.* 2000) and is known to host a relatively low luminosity OHM (Baan *et al.* 1987; Martin *et al.* 1988). Its structure has not been imaged at high angular resolution before, neither has the exact nature of the nuclear power source been determined. The centre of Zw049 was first classified as a starburst based on optical spectroscopy (Baan *et al.* 1998), but has later been suggested to host an AGN due to its radio compactness and spectral index (Baan & Klöckner 2006). Its radio brightness temperature is however consistent with both a compact starburst and an AGN. McBride *et al.* (2013) suggest that Zw049 is in a transition phase between OH megamasers and galaxies with lower luminosity masers. The nucleus is highly dust obscured with luminous vibrationally excited emission from HCN and high surface brightness in the mm continuum (Falstad *et al.* 2015; Aalto *et al.* 2015; Falstad *et al.* 2021). Zw049 fulfills the criteria of a CON and is likely in a phase of rapid nuclear evolution. Falstad *et al.* (2018) find a fast outflow in CO J=6-5, J=2-1 with the Atacama Large mm and submm Array (ALMA), and the Submillimeter Array (SMA), and in cm-wave C-band transitions of OH with the Very Large Array (VLA)).

We have observed the 1665 and 1667 MHz OHM emission with e-Merlin and also the 6 cm formaldehyde H_2CO maser emission (FM). Furthermore we have observed multiple lines with ALMA, including the 265.89 GHz HCN J=3-2 line. *For details on line and continuum fluxes, the physical and chemical conditions, masses, proposed driving forces and structures of the collimated, and slow, outflows of Zw049 please see upcoming journal papers by Wethers et al. and Lankhaar et al. - currently in preparation.* Below are some brief notes on the results.

2.1. *OHM in the complex outflow*

Zw049 appears to have relatively convoluted outflow structure. Falstad *et al.* (2018) detected a fast ($v_{\rm projected}$>300 km s^{-1}) outflow in CO 6-5, 2-1 (in emission) and in cm-wave (4.66, 4.75, 4.77, 6.02, 6.03, 6.03 and 6.05 GHz) OH absorption with the VLA. With recent, very high resolution (0".027 × 0."024 (7 × 6 pc)) ALMA observations we detect luminous HCN J=3-2 emission from a dense ($n > 10^4$ cm^{-2}), collimated molecular outflow (Wethers *et al.* in prep., Lankhaar *et al.* in prep.) (Fig. 1). This is likely the same outflow seen at lower angular resolution in CO 6-5 by Falstad *et al.* (2018), but we find even higher velocities $v_{\rm projected}$=500 km s^{-1}. The dense outflow has an apparent, projected spatial extent of r∼0."25 (∼70 pc) and is collimated where the width is velocity-dependent with the most narrow structure at the highest velocities. Interestingly, using the ESO Multi Unit Spectroscopic Explorer (MUSE) instrument, Wethers *et al.* (in prep.) find an optical outflow on spatial scales at least an order of magnitude larger. The optical outflow also appears to be collimated and its potential relation to the molecular outflow requires further investigation. In addition, Falstad *et al.* (2018) show that there is a radio-jet-like structure extending to the north-west - i.e. not aligned with the molecular outflow. Instead the radio feature appear associated with a narrow dark feature in the HST J-band image (see Fig. 11 in Falstad *et al.* (2018)). This dark feature is either due to dust extinction or to a cloud in the nucleus that blocks radiation (Scoville *et al.* 2000) (if so then much of the minor axis light is scattered from the nucleus).

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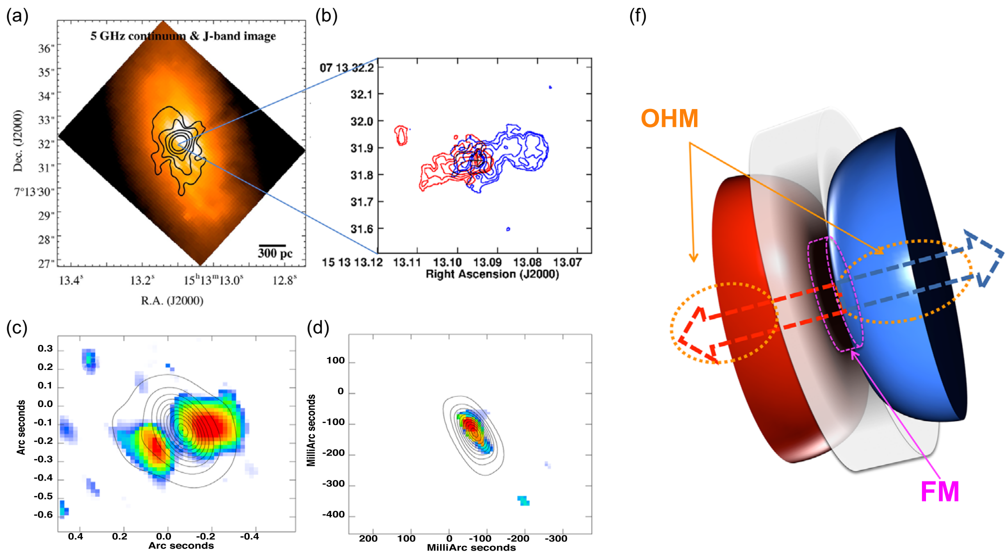

Figure 1. Top left panel **a)** Radio continuum contours overlaid on an HST *J*-band image (Falstad *et al.* 2018). The radio contours are at 1,4,16,64,256 $\times 15 \mu$Jy beam^{-1}. Top centre panel **b)** Preliminary ALMA integrated intensity image of the dense fast and collimated outflow in HCN 3-2 (Lankhaar *et al.* and Wethers *et al.* in prep.). The image is constructed of emission at projected velocities >200 km s^{-1}. Lower left panels: preliminary integrated e-Merlin intensity images of **c)** the OHM line emission (left) and **d)** FM (right). Contours show L- and C-band continuum contours. Right panel: **f)** Preliminary schematic figure of the slow moving wind (in colour) and the fast collimated dense outflow (thick, dashed arrows) of the molecular outflow structure of Zw049. The suggested locations of OH megamaser (OHM) and formaldehyde (FM) megamaser emission are indicated in the figure. High resolution FM emission in Zw049 has previously been reported by Baan *et al.* (2017).

With e-Merlin (resolution 0.″26 × 0.″13 (70 × 35 pc))(Lankhaar *et al.* in prep.), we find that the distribution of the global OHM flux is distributed along the minor axis of Zw049 (Fig. 1). The emission has an east-west velocity gradient with the redshifted velocity to the east and blueshifted to the west with shifts from +20 km s^{-1} to −70 km s^{-1}. This is the same orientation, and size scale, as for the dense collimated molecular outflow, but the velocities are significantly smaller. There is no (or only little) OHM emission associated with the disk or the obscured nucleus.

We propose that the OHM emission is emerging from a larger scale, slower-moving foreground part of the Zw049 outflow. We present a simple cartoon in Fig. 1 of the proposed configuration. We suggest that the OH is pumped by IR emission from the nucleus and/or from the dense outflow. The gas in the CON nucleus is likely too dense for the OHM to operate while van der Walt & Mfulwane (2022) suggest that a FM can operate at $T_{\rm kin} > 100$ K and $n > 10^{4.5}$ cm^{-3}. If so, this explains the FM peak in parts of the CON - while OHM is suppressed in the same region. This opens the possibility of an evolutionary scheme where OHM emission is first suppressed in the LIRG-CON, but then emerges later in its evolution when a dense outflow has developed. ZW049 may therefore not be in transition *out of* an OHM stage, but instead on its way toward higher OHM luminosities when the gas densities in the nucleus have dropped below quenching levels.

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3. OHM and an evolutionary sequence of LIRG-CONs

The LIRG-CONs are characterized by large $N(H_2)$ column densities, high average gas number densities ($n > 10^6$ cm^{-3}), high temperatures ($T > 100$ K,) one (or several) dust-embedded luminosity sources and high IR surface brightnesses (e.g. Aalto *et al.* 2015). The exact process behind the build-up of these large nuclear column densities is not clear. The central gas concentrations may be caused by large inflows of gas in galaxy interactions or mergers, or the return of low angular momentum gas in galactic fountains. The CON region itself is not expected to be a bright OHM source because of the quenching of the OH maser in dense environments. Therefore, in the early, pre-outflow phase of the CON, we do not expect OHM emission. As an outflow develops, OHM action is anticipated to be associated with foreground gas if IR photons can escape from the nucleus along the minor axis. Alternatively, IR emission is emerging from the inner dense outflow itself - providing background pumping emission for the OHM. In this latter scenario, the IR emission would emerge from star formation in the dense gas of the outflow. Such a scenario has yet not been confirmed to exist in outflowing gas (even though there have been suggestions).

The development of an outflow would help drive the evolution of the CON forward through removing gas from the CON-region - reducing the nuclear gas density and opacity. We therefore suggest that OHM is a good tracer of CON-evolution: 1) suppressed in the early pre-outflow stages, 2) then developing in foreground structures linked to the dense outflow, 3) peaking when OHM emission is emerging from both the post-CON nucleus and in structures in the outflow. OHM activity then subsides when gas and dust is dispersed from the central region.

High resolution OHM observations in a sample of U/LIRG CONs, pre- and post-CONs are necessary to test this scenario. It is important to also combine these studies with FM observations, and high resolution mm/submm observations of dense outflows. High resolution OHM observations will also reveal if the CON is surrounded by extended dusty star formation regions that produce OHM emission unrelated to the CON activity. We conclude that it is precarious to generally assume that the OHM emission is associated with disk star formation and that high-resolution OHM observations are key to determine its origin.

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