Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
Proceedings IAU Symposium No. 380, 2024
T. Hirota, H. Imai, K. Menten, & Y. Pihlström, eds.
doi:10.1017/S1743921323002314

The Past, Present, and Groundbreaking Future of OH Megamaser Discoveries

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Abstract. OH megamasers (OHMs) are luminous masers found in (ultra-)luminous infrared galaxies ([U]LIRGs). OHMs are signposts of major gas-rich mergers associated with some of the most extreme star forming regions in our universe. The dominant OH masing line, occurring at 1667 MHz, can spoof the 1420 MHz neutral hydrogen (H I) line in untargeted H I emission line surveys. While only ∼120 OHMs are currently known, H I surveys on next-generation radio telescopes, such as the Square Kilometre Array (SKA) and its precursors, will detect unprecedented numbers of OHMs. This surge in detections will not only fundamentally change what we know about the OHM population, but will also unlock our ability to implement OHMs as tracers of major mergers and extreme star formation on cosmic scales. Here we present predictions for the number of OHMs that will be detected by these surveys. We also present our novel methods for identifying these interlopers using a k-Nearest Neighbors machine learning algorithm. Preliminary data from H I surveys on precursor SKA telescopes is being used to vet and strengthen these methods as well as give us a first look at a new era in OHM science. From a detection of one of the most luminous OHMs to the discovery of a megamaser at a record-shattering redshift, these new sources are glimpses into how our understanding of the known OHM population will soon be expanding and shifting rapidly and how they will influence our understanding of galaxy evolution.

Keywords. OH megamasers, merging galaxies, starburst galaxies

1. Introduction

OH megamasers (OHMs) are rare, luminous 18 cm masers produced in the late stages of major galaxy mergers, generating isotropic line luminosities of $L_{\rm OH} \geq 10\,L_\odot$ with line widths ranging from 10 to 1000 $\rm km\,s^{-1}$. Often, OHMs with line luminosities of $L_{\rm OH} \geq 10^4\,L_\odot$ are referred to as OH *giga*masers but the distinction is arbitrary. This phenomena has only been discovered in ∼120 galaxies and predominantly at redshifts less than $z = 0.265$ (Roberts et al. in prep.). The longstanding record holder for highest redshift was IRAS 14070+0525, discovered by Baan et al. (1992), which held the record from 1992 until 2022.

OHMs are found in (ultra-)luminous infrared galaxies ([U]LIRGs) and are signposts of extreme star formation (Lockett & Elitzur 2008), high molecular gas density (Willett et al. 2011), and strong far-IR radiation (Baan et al. 1989). Though currently rare and known only at limited redshifts, understanding these sources will eventually allow us to study what role these sources play in galaxy evolution, particularly star formation feedback and black hole accretion. Further, as OHMs are found in late-stage major galaxy mergers, they can independently constrain the major merger rate (Roberts et al. 2021). They have also been used as in-situ magnetometers via observations of Zeeman

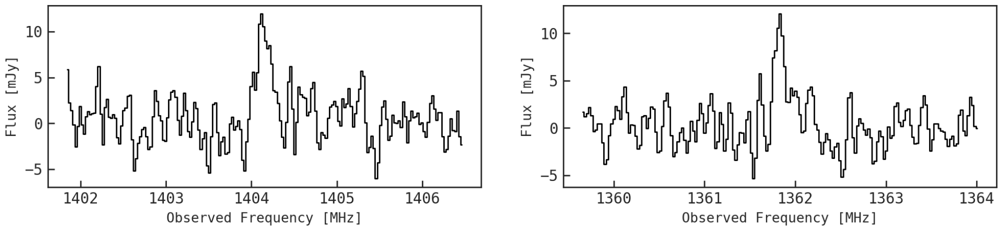

Figure 1. Example spectra from ALFALFA (Haynes et al. 2018) of OH and H I sources – the left panel shows an OH masing line from an OHM host ($\nu_{\rm OH,rest} = 1667$ MHz, $z = 0.188$) and the right panel shows an H I emission line from a non-masing starforming galaxy ($\nu_{\rm HI,rest} = 1420$ MHz, $z = 0.043$).

splitting (Robishaw et al. 2008; McBride *et al.* 2013). Their extraordinary properties and correlation with galaxy mergers make OHMs an invaluable tool for understanding galaxy evolution.

2. The Past: Previous OHM Searches

Despite their apparent utility for tracing major mergers and studying extreme starforming galaxies, efficient methods for finding OHM host galaxies have eluded those searching for them (Roberts et al. in prep.; and references therein). In the 40 years since their discovery, significant efforts have been made to isolate the conditions or properties that can be used to identify OHM host galaxies. However, more has been understood about what is *not* associated with OHMs than with what is associated with them. While OH luminosity ($L_{\rm OH}$) shows good correlation with IR luminosity ($L_{\rm IR}$), ∼80% of (U)LIRGs show no OHM activity (Darling & Giovanelli 2002; Lo 2005). While 50-90% of non-masing (U)LIRGs show evidence of active galactic nuclei (AGN), only 10-20% of OHMs indicate AGN activity (Willett et al. 2011). When it seemed that OHMs may be a distinct class of (U)LIRGs, no optical nuclear distinction could be found between masing and non-masing (U)LIRGs (Darling & Giovanelli 2006). Darling (2007) shows that the dense gas fraction may differentiate between masing and non-masing (U)LIRGs. However, this analysis is only done using eight OHM hosts at a limited redshift range and with unresolved dense gas measurements, requiring further investigation before this distinction can be confirmed. Existing OHMs have been extensively studied and there are still no clear markers of what conditions spur masing action nor what separates masing from non-masing (U)LIRGs.

The majority of past OHM searches have focused on targeting IR-luminous galaxies, which, in conjunction with the fact that only 20% of (U)LIRGs host OHMs, explains the low success rates in these searches. However, with no other properties of the host galaxies clearly distinguishing likely OHM hosts, it is impossible to formulate a more selective method for searching for OHMs. Further, until more are discovered, we lack the ability to entirely understand these sources and use them as tools in studying galaxy evolution.

3. The Present: Development of New OHM Finding Methods

First predicted by Briggs (1998), the 18 cm masing line from an OHM at $z_{\rm OH}$ can "spoof" the 21 cm neutral hydrogen (H I) emission line at a different redshift, $z_{\rm HI}$, if $\nu_{\rm HI}/(1 + z_{\rm HI}) = \nu_{\rm OH}/(1 + z_{\rm OH})$ where $\nu_{\rm HI} = 1420.4$ MHz and $\nu_{\rm OH} = 1667.4$ MHz. The OH and H I emission lines have similar linewidths in their respective environments: H I in spiral galaxies and OH in major galaxy mergers, as shown in Figure 1. For many sources, distinguishing between these lines requires an independent measurement of the galaxy's spectroscopic redshift to determine the rest wavelength for an observed emission line.

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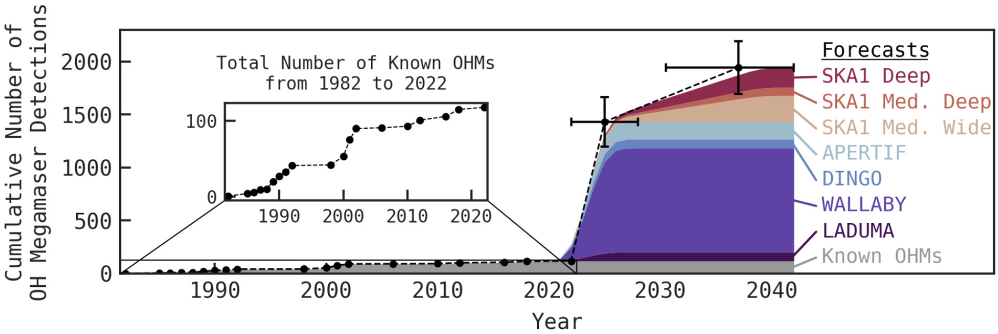

Figure 2. The cumulative number of OHMs detected up to 2023 and forecasts, broken down by current and upcoming H I survey contributions. The two markers with error bars are using projections from Roberts et al. (2021) and the errors in year are estimated using projected dates of survey completion considering typical telescope delays, particularly in the case of the SKA1, whose first light was recently predicted to be in 2027.

As a small demonstration of this, Morganti et al. (2006) fortuitously detected an OHM when searching for H I in galaxies. However, Suess et al. (2016) demonstrated the power of using H I surveys to find OHM hosts by identifying five previously unknown OHMs interloping as H I sources in the 40% data release of Arecibo Legacy Fast Arecibo L-Band Feed Array (ALFALFA; Haynes et al. 2011).

Roberts et al. (2021) presented new methods for flagging potential OHMs in H I surveys using machine learning algorithms and near- to mid-IR photometry. Using these methods, Roberts et al. (in prep.) demonstrates the ability of these methods to find new OHMs by finding five additional OHMs in the full ALFALFA data release (Haynes et al. 2018). These new OHM discoveries, however, are just the beginning.

4. The Groundbreaking Future: The OHM Renaissance in H I Surveys

While finding OHMs in H I surveys is a promising method for expanding the known population of OHM hosts, this method of OHM identification has suffered from limited H I surveys. However, we are currently on the cusp of a new era of H I science with the construction of the Square Kilometre Array (SKA) and its precursors. H I surveys are these telescopes will detect unprecedented numbers of H I sources and, subsequently, OHMs (Roberts et al. 2021). Recent detections from surveys on next-generation radio telescopes highlight this upcoming future. Hess et al. (2021) reports an OHM detection in APERTIF, an H I survey on the Westerbork Synthesis Radio Telescope. This detection presents one of the most luminous OHMs ever found and places an upper limit on the 1612 MHz OH satellite line, making it only the fourth OHM with such a measurement. In addition, the record for highest-redshift OHM was recently shattered with the discovery of an OHM at a redshift of $z = 0.52$ with LADUMA (Looking at the Distant Universe with the MeerKAT Array; Glowacki et al. 2022). However, these two detections are just a small glimpse as the future. Including surveys such as Widefield ASKAP L-band Legacy All-sky Blind surveY (WALLABY) and Deep Investigation of Neutral Gas Origins (DINGO) on the Australian SKA Pathfinder (ASKAP; Duffy et al. 2012), the OHM discovery space will be soon rapidly expanding.

Figure 2 shows projections of OHM detections for a number of H I surveys on SKA precursors as well as fiducial H I surveys of the first phase of the SKA, SKA1. Predictions are obtained from Roberts et al. (2021) which also contains detailed information for each survey. The inset plot shows how past OHM detections evolved in comparison. Even in

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the most conservative estimates, the next two decades of OHM detections will dominate those from the past four decades. In addition to the volume of detections, the quality and diversity of those discoveries will be unmatched, as demonstrated by the recent detections from APERTIF (Hess et al. 2021) and LADUMA (Glowacki et al. 2022). In addition, the tools necessary for identifying interloping OHMs, such as those presented in Roberts et al. (2021), are currently being tested and will be imperative for ushering in this exciting future of OHM science.

5. Conclusions

After forty years of limited OHM detections and discoveries, the era of next-generation H I surveys will be initiating a renaissance of OHM science. Using detections from these surveys in conjunction with novel OHM flagging methods, the number of known OHMs will expand by an order of magnitude, unveiling *thousands* of new sources and fundamentally altering the landscape of what we know about OHMs and their host galaxies. Using this newly expanded, diverse population of OHMs, we will be able to investigate what host galaxy properties are associated with OHMs and potentially finally isolate the mechanisms needed to identify OHM hosts. Further, these sources are science-rich for studying galaxy evolution, extreme star formation, and other host galaxy properties as discussed in these proceedings. This future of OHM detections will unlock the full potential of OHMs as tracers of some of the most extreme conditions in our universe.

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Top; Conference room in the Li-Ka Nangoku Hall. Photographs taken by Ka-Yiu Shum.
Bottom; poster session. Taken by Kaito Kawakami.

https://doi.org/10.1017/S1743921323002314 Published online by Cambridge University Press