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Masers in starburst galaxies

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Abstract. Masers in starburst galaxies are outstanding probes of a range of phenomena related to galaxy and black hole evolution, and offer unique high brightness temperature illumination that can be used to probe small scales in the host galaxy and in our own. But we require a deeper understanding of the galaxy-scale maser phenomenon if we wish to employ starburst galaxy masers as probes using the next generation of radio telescopes. This review summarizes what is known about the different flavors of masers in starburst galaxies and the setting and structure of OH megamasers. The question of which galaxies produce megamasers and which do not is critical to our understanding of the megamaser phenomenon, and recent studies of HCN and H_2CO are particularly instructive. Constraints on the lifetime of OH megamasers and the predictability of OH megamaser line properties are critical issues to address in the near future. It is also time to begin the next wave of OH megamaser surveys at higher redshifts and to finally employ them as probes of starbursts, massive black holes, galaxy evolution, and intervening media.

Keywords. masers, galaxies: starburst, galaxies: nuclei, galaxies: magnetic fields, galaxies: ISM, galaxies: interactions, galaxies: evolution, radio lines: galaxies

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1. The woeful inadequacy of extragalactic observations

Extragalactic maser research is severely hampered by the vast distances between galaxies. While Galactic masers can be observed at AU scales and commonly show flux densities of many — even thousands— of Jy, when we move from kpc to Mpc distances, resolution decreases 1000-fold and sensitivity drops by a million. For the nearest megamaser galaxies, the resolution is another factor of 100 lower, and the sensitivity goes down by 10^4. Thus, AU scales become pc scales in megamaser galaxies and 1 Jy becomes 0.1 nJy. Thanks to distance dilution, Galactic-style masers have been detected only in the Local Group. Enhanced maser emission that is thought to follow a similar mechanism as Galactic masers, the "kilomaser," has been observed in nearby galaxies, such as M82. But for most galaxies in the local universe, modern facilities can only detect "megamasers," masers that do not have Galactic analogs and are extremely rare.

Thanks to distance dilution, extragalactic maser research is information-poor: there are only a few well-mapped systems (pc-scale), only a few hundred megamaser galaxies detected (none beyond $z = 1$), and there are only a few maser species found to date. Unfortunately, the state of the art in extragalactic maser research treats most megamasers and their host galaxies as point sources, and the samples include only the most exceptional systems in the local universe. Megamasers, however, are very bright extragalactic signposts that we need to learn how to read: if we know what these extraordinary phenomena signify (or conversely how they form), then we can employ them as probes of galaxy evolution, star formation, cosmology, and massive black holes.

This review focuses on masers in starburst galaxies (H_2O masers associated with active galactic nuclei are reviewed by Greenhill in this volume), which are mostly OH megamasers (OH MMs; § 2). While examining the setting (§ 3) and structure (§ 4) of OH MMs is instructive, the question of which galaxies produce megamasers and which do not is crucial to understanding the underlying mechanisms behind the megamaser phenomenon in starbursts (§ 5). Examination of other molecular species, both masing and thermal, associated with starburst galaxies is highly instructive in this case. New questions arise (§ 7), but the future looks very promising both in theory and observation for understanding megamasers and employing them as probes of all manner of extragalactic phenomena (§ 8).

2. Extragalactic maser flavors

It is important to remember that *all* masers observed in the Galaxy occur in other galaxies and that the dearth of observed maser species is simply a limitation in sensitivity. Currently, we cannot usually detect the aggregate maser emission from common molecules in external galaxies, much less detect individual maser regions. It is likely that upcoming advances in instrumentation will reveal Galactic-style masing in nearby galaxies outside of the Local Group, and several groups have already detected OH and H_2O kilomasers (e.g., Castangia *et al.*, this meeting).

Currently, observations of extragalactic masers are mostly limited to megamasers, a markedly different phenomenon in scale and setting from Galactic masers or kilomasers. To date, only OH, H_2O, and H_2CO (formaldehyde) have been detected as megamasers. Searches for other common masers, such as CH, SiO, and CH_3OH (methanol), have produced no detections.

In starburst galaxies, the most common megamaser by far is OH. H_2CO megamasers have been detected in a few cases, most notably in the first OH MM discovered and archetypical ultraluminous infrared galaxy, Arp 220 (Baan, Wood, & Haschick 1982; Baan, Güsten, & Haschick 1986), but at about 1% of the intensity of OH MMs (see, e.g., Araya, Baan, & Hofner 2004). We therefore focus primarily on OH MMs in this review.

3. Setting of OH megamasers

3.1. *OH megamaser hosts*

OH MMs are produced in the extreme starbursts occurring during galaxy mergers, apparently favoring late-stage mergers with closely separated nuclei, often in a common envelope. The hosts of OH MMs are (ultra)luminous IR galaxies ([U]LIRGs), and the OH MM fraction is a strong function of the IR luminosity and may depend weakly on far-IR color, favoring "warmer" systems (Darling & Giovanelli 2002a). ULIRGs are roughly as common in the local universe as quasars, and since OH MMs appear in only a fraction of (U)LIRGs, they are exceedingly rare. Large volumes of space ($\sim$1 Gpc^3) have been surveyed in order to detect $\sim$ 100 OH MMs.

It is incorrect to treat OH MM hosts as point sources. Figure 1 shows the illustrative case of IRAS 06487+2208: this OH MM is a multiple-merger system with two optically bright nuclei, two radio continuum sources (only one of which corresponds to an optical nucleus), and an unresolved maser source associated with an optically unremarkable component. The maser source is associated with strong star formation, as expected. Typically, statistical studies of OH MM properties, such as radio continuum, IR luminosity, or optical spectral classification, treat the OH MM and host galaxy as a point source because sub-arcsec angular resolution is not possible. But one should always bear in mind that most OH MM samples are contaminated by non-masing nuclei, and some wavelengths may not even detect the regions responsible for the maser action.

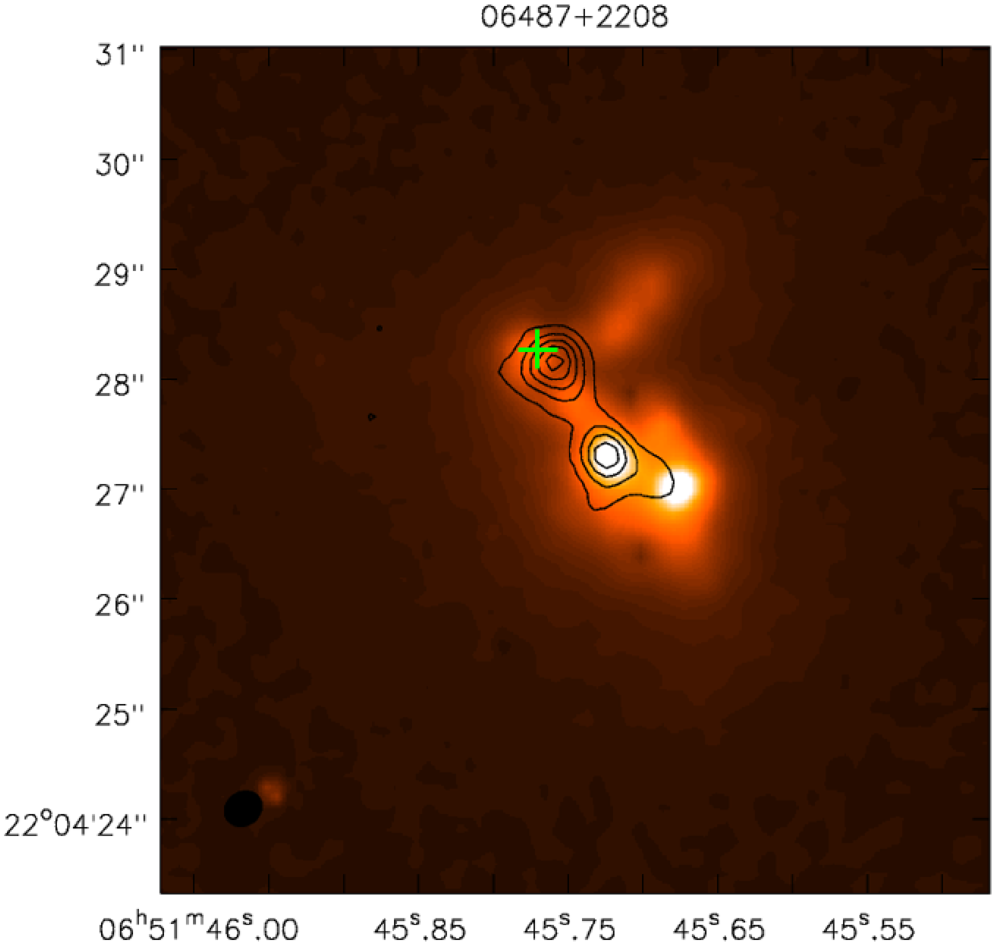

Figure 1. IRAS 06487+2208 (z = 0.1437). The image is from the Hubble Space Telescope (WFPC2 F814W filter: $\lambda = 7940$ Å, $\Delta\lambda = 1531$ Å), revealing sub-arcsec structure. The contours are 5 GHz radio continuum from the VLA, and the cross marks the location of the unresolved OH megamaser emission. The offset between the OH emission and the upper continuum peak should not be construed as significant. Coordinates are J2000.

3.2. *OH megamasers and binary massive black holes*

The evolution of massive black holes in galaxies is merger- and accretion-driven, and both processes are expected to spike during galaxy merging events, so OH MM studies give us a window on this interesting episode in the life of a massive black hole. Of great interest is the emission of gravitational waves by hard binary black holes with sub-pc separation (Begelman, Blandford, & Rees 1980), but the demographics of this population is unknown. Whereas massive galaxies are all thought to harbor massive black holes, whereas a merger has as its inevitable evolutionary outcome a hard binary (i.e., the stalling problem can be surmounted, and neither galaxy already contains a binary massive black hole), and whereas OH MMs occur during a specific stage in merging, therefore OH MMs sample the population of gravitational wave-emitting binary massive black holes with the same lifetime as the OH MM lifetime, as shown in Figure 2. Surveying the population of OH MMs versus redshift thus samples this population of massive black

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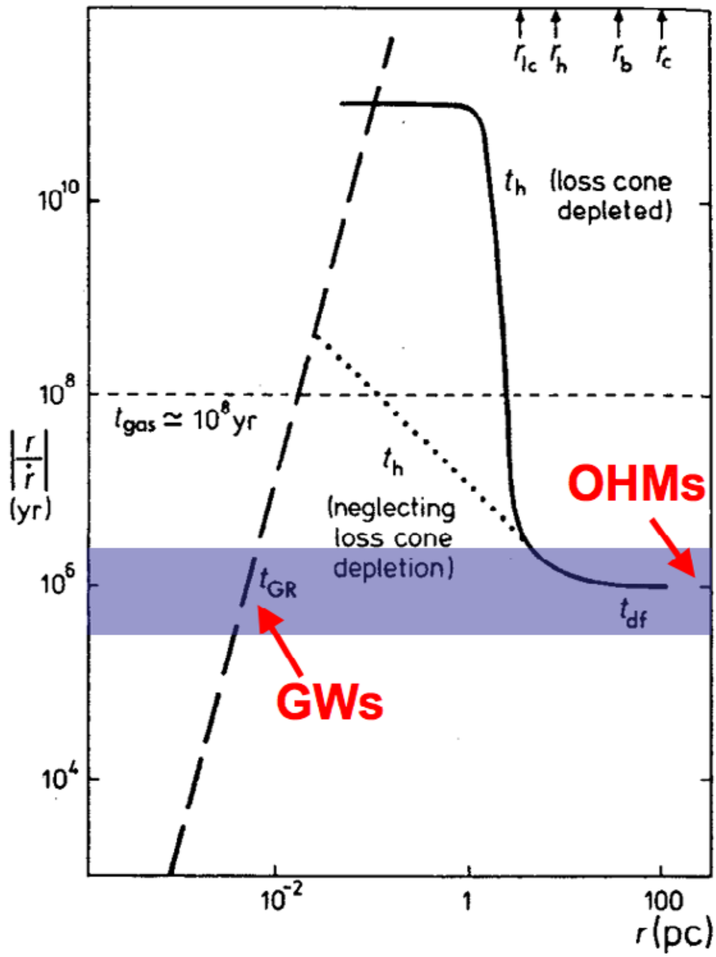

Figure 2. Evolutionary sequence of binary massive black holes from Begelman, Blandford, & Rees (1980). The dashed line indicates the gravitational wave-emitting track leading to coalescence, and the solid line indicates the evolution of the pair by dynamical friction. The arrows and shaded region have been added to emphasize the characteristic timescale sampled by OH MM surveys.

hole binaries. Since the evolution of binaries on the gravitational wave-emitting track is well-defined, OH MM surveys will furthermore provide a census of a large fraction of the hard binary massive black hole population. The missing elements for this type of study are the OH MM lifetime and surveys for redshifted OH MMs (see § 8).

4. Structure of OH megamasers

4.1. *Theory*

There is an encouraging convergence of the theory behind OH MM formation thanks to work by, among others, Parra *et al.* (2005; this volume) and Lockett & Elitzur (2007; this volume). There are, however, areas where observations can confront the theory and make it robust. Observers need to expand the sample of OH MMs with 18 cm satellite line measurements because Lockett & Elitzur (2007) make firm predictions in this area. It will be interesting to see if observed constraints on maser brightness temperatures, particularly those at high redshift showing variability (§ 4.3), can be reproduced by models. There are also new hints of a critical H_2 density for OH MM formation that should be explored with maser models (§ 5).

4.2. *Clues from VLBI*

The fundamental units of maser action, unimaginatively called "spots" (the author proposes a new term: "mason"), are notoriously difficult to resolve, even with very long baseline interferometric (VLBI) observations. The rarity of OH megamasers places them at large distances, which compounds the resolution problem. Addressing such basic issues as where OH MMs are produced in merging systems, their spatial extent, how the emission geometries relate to line profiles and merger kinematics, and the relationships between OH MMs and optical spectral types of nuclei, are exceedingly difficult with modern instrumentation. A handful of the closest OH MMs have been studied in some detail: the most recent observations include III Zw 35 by Pihlström *et al.* (2001); Arp 220 by Rovilos *et al.* (2003); Mrk 231 by Klöckner, Baan, & Garrett (2003); Mrk 273 by Yates *et al.* (2000) and Klöckner & Baan (2004); and *IRAS* 17208−0014 by Momjian *et al.* (2006). The sample size remains small and the results of these studies generally indicate that many of the details of OH MMs remain hidden from view by their small sizes and low fluxes.

VLBI studies do appear to have converged on some aspects: OH is observed in 1–200 pc structures; CO and HI are more extended and mostly exterior to OH; a large fraction of the sample shows toroidal OH MM regions with thickness of the same order as the height and velocity dispersion roughly equal to rotation (e.g., III Zw 35); and line widths remain large on the smallest observed scales. But the small VLBI sample remains extremely diverse, ranging from nearly pure starbursts to Sey 1 AGN. Of particular richness are recent observations of the OH, both in emission and absorption, in Arp 220 toward radio supernovae (Lonsdale *et al.* this volume).

4.3. *Variability in OH megamasers*

Variability was discovered in OH MMs by Darling & Giovanelli (2002b) with properties consistent with refractive interstellar scintillation (ISS). Further study of a sample of OH MMs over long timescales is underway (Darling 2007b). Variability in these spectral line sources offers a powerful super-VLBI probe of OH MM structure because not all spectral line components vary, and those that do vary do not always vary together. There is a critical threshold angular size scale above which the scintillation of radio waves induced by the Galactic free electrons washes out and below which the observed scintillation can be quite strong and rapid. Applying an ISS model to the observed variability allows us to segregate maser component size scales based on the presence or absence of variation and the magnitude of fluctuation and to segregate positions of masing regions on the sky based on correlation (or not) of variations in scintillating components. For OH MMs, one can obtain sub-milliarcsecond "resolution" from this approach and significantly constrain the brightness temperature of OH MM spots.

An interesting case study is IRAS 02524+2026 at $z = 0.18$, which has been observed as part of an OH MM monitoring campaign at Arecibo (Darling 2007b). This OH MM shows strong variability in many spectral components in both of the "main" 18 cm OH lines (Figure 3). The rms spectrum significantly understates the day-to-day variation seen in this source. Preliminary analysis suggests that variable features are smaller than ~ 1 pc (0.3 mas), which implies a brightness temperature $T_b > 8 \times 10^{11}$ K. We observe spectral components that vary together, implying coincidence on the sky, and components that are uncorrelated, implying some minimum separation on the sky.

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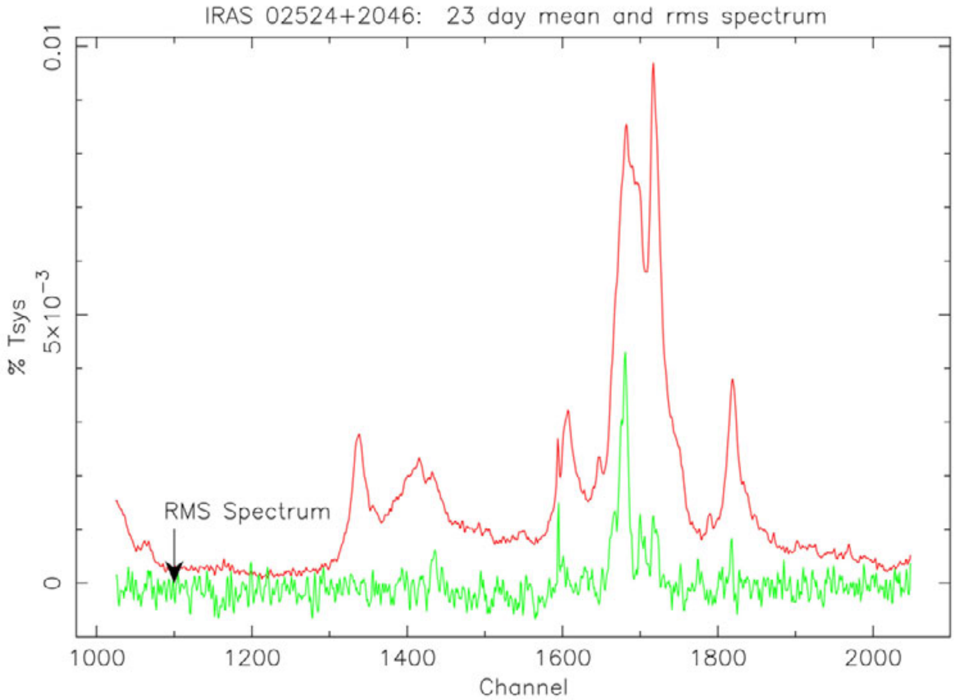

Figure 3. IRAS 02524+2046 ($z = 0.18$) observed at Arecibo in a variability monitoring campaign. The red spectrum is the 23-day mean and the green spectrum is the rms over the same interval. Both of the "main" 18 cm OH lines show variation.

4.4. *Magnetic fields*

Robishaw (2006; this volume) has detected Zeeman splitting in several OH MM galaxies, from Arp 220, which shows many polarized line components, to IRAS 12032+1707 at $z = 0.217$. IRAS 12032+1707 shows variability in at least two line components (Darling 2007b), one of which corresponds with the polarized component identified by Robishaw (personal communication). This is an exciting new result: the variable feature, if it is due to ISS, is smaller than about 1 pc across. What does this imply about the magnetic field strength and density across the maser emission region?

It is likely that coupled with VLBI observations, modelling, and variability studies, detections of Zeeman splitting in OH MMs will provide new insight into OH MM physics and the associated ISM in distant interacting starburst galaxies.

5. Who mases?

5.1. *Searches for differences*

Lo (2005) posed a key question critical to our understanding of OH megamasers: why do 80% of luminous IR galaxies show no OH MM activity? To reframe the question: take two merging systems with similar global IR and radio continuum properties in the same morphological stage of merging; one shows OH MM emission while the other does not. Why? What is the difference between the two systems? Perhaps there is no difference and the fraction of OH MMs among mergers simply reflects beaming. Or perhaps OH MM activity depends on small-scale conditions that are relatively decoupled from global

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properties of mergers (remember that in most studies, OH MM samples are completely unresolved).

Several groups have investigated this issue with studies of IR, radio, and optical properties of samples of OH MMs and non-masing systems. For example: Baan, Haschick, & Henkel (1992) and Darling & Giovanelli (2002a) have investigated the OH MM fraction in (U)LIRGs versus star formation rate and IR color; Baan, Salzer, & LeWinter (1998) and Darling & Giovanelli (2006) used optical spectral classification to distinguish populations and quantify AGN fraction in OH MM hosts; Darling & Giovanelli (2002a) and to a much greater extent Baan & Klöckner (2006) studied radio and IR properties vis-a-vis the AGN versus starburst contributions to OH MM activity; and Vignali *et al.* (2005) conducted an X-ray study of the contribution of AGN to OH MM hosts. While some of these studies pointed to some small differences in statistical samples of OH MM hosts versus non-masing systems, they could not identify in a case-by-case basis which systems would harbor OH MMs and which would not based on any observable quantity except the OH line itself.

These types of studies are complicated by the fact that in most cases, multiple-nucleus merging systems are not resolved: masing nuclei are contaminated by non-masing nuclei within mergers, and the optically dominant nucleus is often not the masing nucleus (Figure 1). So even if there were global properties of starburst nuclei that are responsible for OH MM production, it is likely that these properties will not be identifiable without sub-arcsecond resolution in the IR and optical regimes.

5.2. *Lessons from HCN*

Let us diverge from OH for a moment to discuss recent studies of HCN in nearby starburst galaxies. HCN is a high density tracer of molecular gas ($n(\mathrm{H_2}) \gtrsim 3 \times 10^4$ cm^{-3}), shown by Gao & Solomon (2004) to correlate in a linear fashion with star formation (proxied by IR luminosity), even in ULIRGs where the CO line saturates. Gao & Solomon (2004) show that the population of CO-saturated ULIRGs have an extreme dense gas fraction, as measured by $L_{\mathrm{HCN}}/L_{\mathrm{CO}}$. Darling (2007a) show that while OH absorbers in the Gao & Solomon sample appear nearly uniformly distributed in L_{IR} and L_{HCN}, OH MMs represent the *majority* of the CO-saturated population. It appears that OH MMs form the bulk of the high dense gas fraction starbursts and that we can at last observe a quantity ($L_{\mathrm{HCN}}/L_{\mathrm{CO}}$) that is highly predictive of OH MM activity. This is consistent with the modelling work by Parra *et al.* (2005) showing that the critical component for OH MM formation is cloud-cloud overlap; a galaxy-scale high dense gas fraction provides the required overlap of many dense clouds. Moreover, OH MMs are thus signposts of the most extreme star formation in the local universe: surveys for OH MMs will now provide more information about the detected host galaxies and their mode of star formation. These issues are discussed in detail in Darling (2007a).

5.3. *Lessons from H_2CO*

One more divergence to examine formaldehyde ($\mathrm{H_2CO}$). The most commonly observed line is the ground state cm transition of ortho-$\mathrm{H_2CO}$ at 4.8 GHz. Empirically, there are two flavors of extragalactic formaldehyde seen in starburst galaxies: in "normal" starbursts, this line is seen in absorption ostensibly against the starburst radio continuum, but in OH MM galaxies, this line appears in emission. To date, *all* confirmed extragalactic $\mathrm{H_2CO}$ masers are also OH megamasers and *all* $\mathrm{H_2CO}$ absorbers are also OH absorbers (Araya *et al.* 2004; Mangum *et al.* 2007; Darling & Mangum 2007). Recent modelling of $\mathrm{H_2CO}$ lines and line ratios by Mangum *et al.* (2007) shows that this flip in the ground state line can be explained entirely by collisional excitation. The excitation of $\mathrm{H_2CO}$ cm lines thus depends critically on $n(H_2)$, and the flip occurs at roughly $n(H_2) \sim 10^{5.6}$ cm^{-3}. If this correlation between OH and H_2CO holds, then the notion of a critical density for OH MM formation plus the galaxy-wide molecular gas concentration suggested by HCN studies gives us new insight into the OH MM process and allows us to predict the presence or absence of OH MMs based on the fundamental properties of a given starburst. The new insight into OH MMs provided by H_2CO is discussed in detail in Darling & Mangum (2007).

6. An emerging picture?

Pulling all of these threads in the OH MM story together, we can weave a first-order tapestry of the setting and process of OH MM formation. During interaction and merging of two (or more) massive gas-rich galaxies:

(1) Tidal torques move gas into radial orbits, depositing a large fraction (of order half) of the gas into the nuclear regions (inner ∼kpc) and throwing much of the remaining gas into tidal tails.

(2) There is (often, but perhaps not always) a stage of extreme dense gas fraction in the nuclear starburst, presumably due to radially infalling gas.

(3) During this high dense gas fraction stage, the fraction of clumps with the requisite density range for OH masing is strongly enhanced, providing enough cloud-cloud overlap for stochastic maser amplification.

(4) Maser emission, while beamed, is stochastic, implying that the OH MM would be viewed as such from most directions.

It is appropriate to think of OH MMs as a transient phenomenon during major mergers, which is why constraining the lifetime of OH MMs is critical to employing them as tracers of extreme stages of star formation. Given the OH MM fraction in starbursts, constraints on the OH MM lifetime will indicate the fraction of mergers that go through the extreme starburst stage. Clearly understanding OH MMs goes beyond the maser itself and has fundamental applications to galaxy evolution and the formation of stars in bursts.

7. New questions

While we may now be able to predict which galaxies show OH MM activity, several questions remain before OH MMs can be employed as effective tracers of galaxy and black hole evolution:

• Can the OH MM line luminosity and profile can be predicted? If we can find a connection to the OH MM line properties, then OH MMs become a very powerful probe of the detailed conditions of star formation at cosmological distances.

• What is the OH/H_2CO megamaser lifetime? Constraints on the OH MM lifetime will provide a connection to the star formation history in giant ellipticals and a connection to gravitational waves produced by the binary massive black hole population.

• What is the physics of OH MM activity? Do OH and H_2CO arise in the same regions? Why is there a density threshold for OH MMs? Models are key, given new observational inputs.

8. The future

It is time to break the OH MM redshift record held by IRAS 14070+0525 at $z = 0.265$ (Baan *et al.* 1992) and to employ OH MMs as tracers of galaxy, black hole, and star formation evolution to their full potential, particularly as we gain a deeper understanding

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of what OH MMs signify. There are barriers and boons to OH MM searches at high(er) redshifts. Barriers include radio frequency interference (RFI) — which will be disastrous once the conversion to digital television is complete — limited receiver coverage below 1100 MHz particularly on interferometers that can spatially filter RFI, and the simple rarity of OH MMs in the universe. But many of these barriers can be overcome by the boons of increased star formation and merging activity in the past, telescope sensitivity adequate for detections of known OH MMs out to $z \sim 1$, and the fact that roughly half of known OH MMs are quasar-like in the sense that they are "overluminous" compared to a typical flux-limited sample. That is, they could be detected at many times their actual redshift in the short integration times of the Arecibo OH MM survey (Darling & Giovanelli 2002c). If a survey can reach a 5σ sensitivity of 1 mJy in ~ 10 km s^{-1} channels, then OH gigamasers can be detected out to $z \sim 1$ and OH MMs with $L_{\rm OH} > 10^3 L_\odot$ can be detected up to $z = 0.5$ (Darling & Giovanelli 2002c). An obvious sample for targeted observations is the submm galaxies, which are known to have extreme star formation rates and ample molecular gas.

It is also essential to constrain the lifetime of OH MMs in order to understand the role and significance of the OH MM/extreme starburst phase in major galaxy mergers. The OH MM lifetime has implications for nearly all applications of OH MMs as signposts of mergers including the merging history of galaxies, the stellar mass created in mergers, the growth of massive black holes, and the gravitational wave-producing population of massive black hole binaries.

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References

Araya, E., Baan, W. A., & Hofner, P. 2004, *ApJS* 154, 541
Baan, W. A., Wood, P. A., & Haschick, A. D. 1982, *ApJ* 260, L52
Baan, W. A., Güsten, R., & Haschick, A. D. 1986, *ApJ* 305, 830
Baan, W. A., Haschick, A. D., & Henkel, C. 1992, *AJ* 103, 728
Baan, W. A., Rhoads, J., Fisher, K., Altschuler, D. R., & Haschick, A. D. 1992, *ApJ* 396, L99
Baan, W. A., Salzer, J. J., & LeWinter, R. D. 1998, *ApJ* 509, 633
Baan, W. A. & Klöckner, H.-R. 2006, *A&A* 449, 559
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, *Nature* 287 307
Darling, J. & Giovanelli, R. 2002a, *AJ* 124, 100
Darling, J. & Giovanelli, R. 2002b, *ApJ* 569, L87
Darling, J. & Giovanelli, R. 2002c, *ApJ* 572, 810
Darling, J. & Giovanelli, R. 2006, *AJ* 132, 2596
Darling, J. 2007a, in preparation
Darling, J. 2007b, in preparation
Darling, J. & Mangum, J. G. 2007, in preparation
Gao, Y. & Solomon, P. M. 2004, *ApJ* 606, 271
Klöckner, H.-R., Baan, W. A., & Garrett, M. A. 2003, *Nature* 421, 821
Klöckner, H.-R. & Baan, W. A. 2004, *A&A* 419, 887
Lo, K. Y. 2005, *ARAA* 43, 625
Lockett, P. & Elitzur, M. 2007, in preparation
Mangum, J. G., Darling, J., Menten, K. & Henkel, C. 2007, in preparation
Momjian, E., Romney, J. D., Carilli, C. L., & Troland, T. H. 2006, *ApJ* 653, 1172
Parra, R., Conway, J. E., Elitzur, M., & Pihlström. Y. M. 2005, *A&A*, 443, 383

Pihlström, Y. M., Conway, J. E., Booth, R. S., Diamond, P. J., & Polatidis, A. G. 2001, *A&A* 377, 413

Robishaw, T. 2006, *BAAS* 209, #198.06

Rovilos, E., Diamond, P., Lonsdale, C. J., Lonsdale, C. J., & Smith, H. E. 2003, *MNRAS* 342, 373

Vignali, C. Brandt, W. N., Comastri, A., & Darling, J. 2005, *mnras* 364, 99

Yates, J. A., Richards, A. M. S., Wright, M. M., Collett, J. L., Gray, M. D., Field, D., & Cohen, R. J. 2000, *MNRAS* 317, 28