Part Vb. OH MASERs

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Cosmic MASERs: From Protostars to Blackholes
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OH megamasers

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Abstract. The history of OH megamaser (OHM) research is reviewed, and recent developments in the field are summarized. Particular attention is paid to results from VLBI, and the recognition of a wide range of maser properties within a single galaxy. A peculiar characteristic of compact parsec-scale OHM features is a very broad velocity width, which poses a challenge for radiative pumping models, and suggests filamentary geometries for the emitting clouds. The compact masers may be associated with shocks in a violent nuclear environment, and collisional pumping may play a role. A link between the compact masers and newly formed active galactic nuclei (AGNs) cannot be ruled out. The low-gain amplification model of the diffuse maser component is strongly supported by recent data, and detailed information about the parameters of the amplifying screen is starting to emerge. OHM can be used as powerful probes of dusty, obscured IR galaxy nuclei, and the prospects for these objects being detectable, and therefore useful as probes, at cosmological distances is discussed.

1. Introduction: Basic OH Megamaser Properties

The field of OHMs was born in 1982, with the publication of a hydroxyl spectrum (Figure 1) of the peculiar galaxy Arp 220 (IC4553) by Baan, Wood and Haschick (1982). Under the assumption of isotropic emission, the luminosity of the Arp 220 masers exceeded that of typical galactic OH masers by a factor of more than 10^6, leading to the term "megamaser". The velocity width of the maser emission is a few hundred km/sec, also quite different from galactic OH masers. Finally, the Arp 220 emission is dominated by the 1667 MHz main line. The 1665 MHz main line is present at about 20% of the strength, and later observations (Baan and Haschick 1987) showed that weak satellite line emission at 1612 MHz and 1720 MHz is present. These line ratios differ markedly from those of previously known galactic maser regions, reflecting different physical conditions in the OH gas, and different pump characteristics.

These basic properties are common to most OHMs. The 1667/1665 line ratio varies widely from system to system, but the value of 5 found in Arp 220 is typical. The line profiles, once thought to be characteristically double-peaked, in reality show a wide variety of shapes, often quite complex. This variety can be seen in the recent survey of Darling and Giovanelli (2000, 2001).

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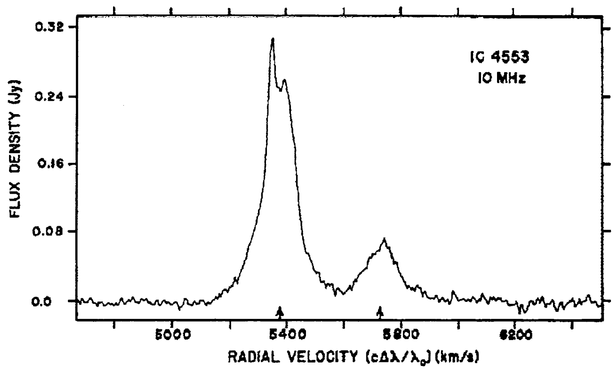

Figure 1. Arecibo OH spectrum of Arp 220, taken from Baan, Wood & Haschick 1982

1.1. The Standard Model

Through the mid-1980s, the number of known OHM galaxies slowly grew, with the addition of Mrk 273 (Baan, Haschick and Schmelz 1985, Bottinelli *et al.* 1985), Mrk 231 (Baan 1985, Kázes and Dickey 1985), NGC3690 (Baan 1985), III Zw 35 (Staveley-Smith *et al.* 1987), IRAS 17208-0014 (Bottinelli *et al.* 1987) and 11506-3851 (Norris *et al.* 1986). During this period, in conjunction with the findings of the pioneering IRAS satellite, it was realized that the OHM phenomenon is closely associated with the luminous far-infrared (FIR) galaxy phenomenon, characterized by intense far infrared and radio synchrotron emission from the nuclear regions. This led to the formulation and refinement of a megamaser model based on low-gain unsaturated maser action, amplifying the background radio continuum synchrotron radiation from the galaxy nucleus. In this model, maser clouds occupy a large volume of space in and around the nucleus of the galaxy. The intense far-infrared radiation field from the nucleus, a defining property of the FIR galaxies, causes radiative pumping of the OH main lines via some combination of transitions at 35, 53, 79 and 119 μm. The required pump photon efficiencies for such a model did not exceed ~1% for any known megamaser galaxy.

The unsaturated low-gain (amplification ratio $S_{1667}/S_{continuum} \sim 1$) diffuse-screen OHM model was presented by Baan (1985), and has seen significant subsequent refinement (Henkel and Wilson 1990, Randell *et al.* 1995). As discoveries of megamasers accelerated in the late 1980s, a clear relationship between OH luminosity and FIR luminosity became apparent, with $L_{OH} \propto L_{FIR}^2$ (e.g. Martin *et al.* 1988). This relationship is readily integrated into the low-gain amplification model, since the radio continuum being amplified is proportional to the far IR luminosity (via the well-established radio-FIR relationship). The quadratic L_{OH}/L_{FIR} relationship then implies a quite plausible linear relationship between the number of inverted OH molecules participating in unsaturated maser amplification, and the number of FIR photons.

Since the OH emission results from a diffuse amplifying screen in this model, and since the radio emission in megamaser galaxies is known to be dominated by a diffuse component extended on 0.1 arcsec scales (e.g. Condon *et al.* 1991), the model makes a clear prediction that the OH emission should also be diffuse on these scales. The velocity width of the OH line is interpreted in terms of the overall rotation of the host galaxy, which should be evident given imaging observations of sufficient sensitivity and resolution.

The main-line ratio 1667/1665 is predicted to depart from the LTE value of 1.8 according to the OH opacity, with higher opacities giving rise to higher 1667/1665 ratios. Combining this with a covering factor thought to be much less than unity, estimates of maser cloud properties as a function of observed line ratios are possible (Randell *et al.* 1995). Not all nearby luminous FIR galaxies exhibit detectable OH emission, and the detection fraction is a function of FIR luminosity. This has led to speculation that the OH-bearing interstellar medium in these galaxies is confined to a disk or torus, whose solid angle subtended from the nuclear diffuse continuum source is significantly less than 4π steradians. This solid angle is implied to increase with luminosity, approaching 4π at FIR luminosities above $10^{12} L_{\odot}$.

1.2. Some Additional Properties

Consistent with the hypothesis of an infrared, radiative pump, OHM properties appear to be related to the FIR colours, in the sense that warmer and more luminous systems tend to be maser sources, while cooler less luminous systems tend to be OH absorbers (Baan 1989). This behaviour suggests that the number of 35 μm and 53 μm photons is important to the OH pumping. Further information on the pumping mechanism is provided by observations of absorption in the FIR pumping lines using ISO (e.g. Skinner *et al.* 1997), and the assumption has been that these photons are being absorbed by the same OH molecules that become inverted and lead to maser emission in the radio.

In Arp 220, Baan and Haschick (1987) have found evidence for multiple velocity components, including weak emission at velocities approaching 1000 km/s. In addition, some megamaser sources display line velocity widths of up to 1500 km/s (e.g. 12032+1707, Darling and Giovanelli 2001). Clearly, OHM galaxies are sites of violent motions, traced by the line emission. There is evidence, from single-dish data, that line ratios differ markedly between different velocity components in the same object, suggesting that their locations and physical environments are different.

OHMs may be associated with formaldehyde (H_2CO) maser activity (Baan, Haschick and Uglesich 1993). Surprisingly, however, they appear to be mutually exclusive with water megamasers, which are closely associated with AGNs. It is likely that water and OH megamasers occur at different phases of nuclear activity in galaxies (for discussion of galaxy mergers, and evolution of nuclear activity, see section 3.3). Rotationally excited OH has been seen in absorption in OHM systems (Henkel, Güsten and Baan 1987), which can be readily incorporated into the standard model of diffuse low-gain amplification for the masers.

2. VLBI Surprises

A clear prediction of the standard model is that the maser emission structure will be closely related to the background continuum emission being amplified. In particular, since the masing screen is postulated to be diffuse on scales of order 100pc, VLBI-scale OH emission on parsec-scales would have to represent amplification of similarly compact continuum structures. This was indeed the interpretation of the first compact OH structures found in Arp 220 by Diamond *et al.* (1989), using narrow-band (MkII, 2MHz) VLBI on relatively short intra-European baselines. They found two regions of compact emission, one in each nucleus, but the experiment was insensitive to continuum emission, and the results were consistent with the standard model, on the assumption that undetected compact continuum sources were present behind the observed OH features.

2.1. Parsec-scale masing structures

The first clear evidence that the situation was more complicated came from a wide bandwidth VLBI experiment with intercontinental baselines and good continuum sensitivity (Lonsdale *et al.* 1994). These data demonstrated that in Arp 220, much of the OH flux density originated on parsec-scales, and that correspondingly compact continuum emission was nearly two orders of magnitude weaker, setting a lower limit to the maser amplification factor of around 60, and calling into question the general applicability of the standard model. Further progress, however, demanded full VLBI imaging of the emission to clarify the spatial relationship, if any, between line and continuum.

In late 1994, a 17-telescope global VLBI array was assembled and used to observe four bright OHM galaxies, namely Mrk 231, III Zw 35, IRAS F17208 and Arp 220. OH maser images were produced for all sources except Mrk 231, in which the emission was completely resolved out by the array. Ironically, Mrk 231 is the one source in the group which exhibits strong compact continuum emission, and which would have been expected to show compact OH emission in a low-gain amplification model. The results on the other three sources dramatically confirmed the presence of very high amplification factors, and ruled out the standard model as a complete explanation of the OHM phenomenon.

The most illustrative example comes from Arp 220, the brightest maser spot in which is less than 1 parsec across, and which occupies a region devoid of any detectable continuum emission. A lower limit to the line/continuum ratio at this location is 800. Many other features in Arp 220 and other sources exhibit lower limits to this ratio which are inconsistent with the low-gain amplification proposed in the standard model. Such high ratios, in fact, combined with observed OH brightness temperatures of up to 10^{10}K, strongly suggest saturated maser action, instead of the unsaturated maser clouds in the standard model. These results appear in Lonsdale *et al.* (1998), and Diamond *et al.* (1999).

It is most important to note that these VLBI studies reveal the properties of emission on milliarcsecond angular scales, but are not sensitive to more diffuse emission. Generally, only about half of the total OH flux density of these objects is detected in VLBI experiments, which presumably corresponds to localized regions of very strong maser action. The properties of more diffuse emitting regions cannot be directly addressed using VLBI, with one startling exception. In general, the VLBI-scale OH emission is not associated with compact continuum sources. However, in Arp 220 about a dozen sub-mJy unresolved continuum sources were detected, which are interpreted as recent radio supernovae (RSN, Smith *et al.* 1998). Two of these sources show precisely positionally coincident OH spots, with an apparent amplification ratio of 5. Further, one of the OH spots shows two distinct velocity peaks separated by 160 km/s. These spots dramatically confirm the existence of an unsaturated amplifying screen with properties similar to those postulated in the standard model, in at least some regions of the source.

2.2. Velocity widths

A major surprise from the VLBI imaging was that on even the smallest angular scales, the maser features exhibit very broad velocity widths, typically several tens of km/sec, and up to 150 km/sec. This behaviour is in sharp contrast to expectations, and challenges radiative pumping models (see next section). Typically, as angular resolution increases, emitting maser spots comprise fewer individual maser gain paths, and are thus characterized by progressively narrower and spikier line profiles. Such an effect is notably absent in compact OHM structures. In Arp 220, a major part of the velocity width of the integrated line profile originates on sub-parsec scales, contradicting the previous assumption that large-scale motions and galaxy rotation were solely responsible for these widths. This phenomenon, combined with the fact that the spots remain substantially unresolved by VLBI, suggests extraordinarily large transverse velocity gradients, as projected onto the sky plane, with lower limits of several tens of km/s/pc. The origin of such apparent gradients, and the role of geometrical projection effects, remain to be explored. In the few cases where strong small-scale velocity gradients have been resolved (Lonsdale *et al.* 1998; Diamond *et al.* 1999), patterns which suggest orbital motion, presumably around massive condensed objects, have been seen. However, these data may not have enough angular resolution to avoid problems with velocity blending, similar to those which affected earlier results (e.g. Montgomery & Cohen 1992).

Clearly, some megamaser galaxies show evidence of violent motions, with total velocity widths exceeding 1000 km/s. It is important to discover whether such extreme widths originate in large-scale motions such as superwind outflows, or whether they too reflect unexplained steep small-scale velocity gradients.

2.3. Additional new results

The ubiquity of parsec-scale emission in OHM sources is suggested but not proved by current VLBI information, in large part due to sensitivity limitations; only the nearest and strongest OHM sources have yet been studied in detail with VLBI. An additional difficulty is that the L-band receivers of many VLBI telescopes cannot accomodate the redshifted OH line frequencies of more distant megamaser galaxies. However, Darling and Giovanelli (2001) report widespread variability among the many distant megamasers in their sample. Compactness is implied by variability, whether or not such variability is intrinsic to the emission regions, or is the result of interstellar scintillation. This result strongly supports the conclusion that strong, parsec-scale features are a common, possibly universal, component of OHM sources. Certainly, any complete OHM model must account for the compact component of the emission.

The disposition and nature of the diffuse maser emission component is clarified by two new results presented in this volume, by Pihlström, Conway and Booth, and by Klöckner & Baan. Both of these papers describe medium-resolution imaging of OHM galaxies, revealing the location and velocity structure of relatively diffuse OH emission, extended on scales of 0.1 arcsec. These data are consistent with rotating molecular disks in which the inverted OH resides, and lend direct support to the standard model as an explanation of the diffuse OH maser component. One of the galaxies observed by Klöckner & Baan, Mrk 231, is remarkable in that no compact OH emission is present, despite a strong, compact AGN-related continuum radio source. This fact can provide insight into a possible evolutionary picture of luminous IR galaxies and OHMs (see below).

3. OH megamaser models

3.1. The diffuse component

On scales greater than ~0.1 arcsec, OHM emission displays properties fully consistent with the standard model. Accounting for a large fraction of the total OH luminosity, this emission appears, at least in some sources, to arise primarily in rotating disks or tori. Previously mentioned diagnostics of the far IR radiative pumping, such as FIR absorption lines, and excited state absorption at cm wavelengths, almost certainly probe the properties of OH molecules involved in the generation of the diffuse component, and not of the compact maser emission.

A pressing question regarding the diffuse component is its relationship to the more mysterious compact component. Recent data demonstrate that at least in sources studied to date with sufficient detail, compact masers are always embedded in regions of more diffuse emission, and never appear as isolated spots. There appears to be a continuum of structures linking the diffuse and compact emission. If this proves to be a general property of OHMs, it constitutes an important clue to the nature of the phenomenon.

3.2. The compact component and the IR pump problem

Geometry and Pump Photon Efficiency. A given IR pump photon is generally capable of producing no more than a single OH inversion, and thence a single OH maser photon. Realistically, it is unlikely that the pump photon efficiency defined by the ratio of the number of OH to FIR photons at a given velocity, and straightforwardly measured via the ratio of observed flux densities assuming isotropic radiation, can much exceed 1%. Indeed, OH megamaser galaxies display flux density ratios $S_{1667MHz}/S_{60\mu\mathrm{m}}$ generally in the range 10^{-4} to 10^{-2}, comfortably consistent with a FIR radiative pump model (e.g. Henkel and Wilson 1990).

Such a global efficiency, however, ignores the likelihood that a fraction of the isotropically emitted FIR photons will miss the OH bearing clouds altogether, and will be unavailable for pumping. The properties of the compact OH megamaser components suggest physically compact maser clouds, while the physics of dust emission requires a relatively large volume (typically of order 100pc) for the FIR source. The required pump photon efficiency must be divided by the fraction of the FIR photons whose paths intersect the maser clouds.

Consider a spherical maser cloud of radius r, embedded in a spherical, uniform optically thin FIR emitter of radius R. For a deeply embedded maser cloud a distance a from the center of the FIR emitter ($a/R \ll 1$), the fraction

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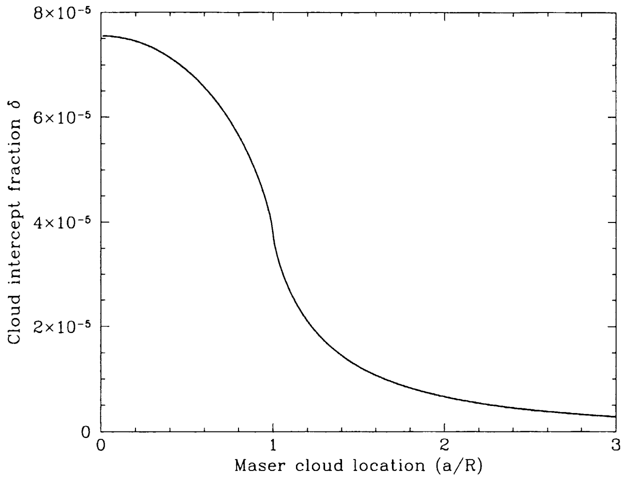

Figure 2. Effects of geometry on radiative pumping. A spherical maser cloud of diameter 1pc, pumped by radiation from an optically thin infrared source of diameter 100pc, will intercept only a small fraction, δ, of the IR photons. Plotted is the fraction δ as a function of the distance of the maser cloud from the center of the IR source. Values of $a/R > 1$ indicate a maser cloud location outside the IR source, and for large a/R, δ asymptotes to an inverse quadratic.

δ of all emitted FIR photons intercepted by the maser cloud is of order $(r/R)^2$. Evaluation of an analytical expression for this δ, over a wide range of values for a, and assuming $r/R \sim 0.01$ based on observations, results in the plot shown in Figure 2.

The peak of the maser spectrum in VLBI-studied sources is typically dominated by one or two compact spots. Therefore, the global pump efficiencies of 10^{-4} to 10^{-2} in OHM galaxies should be within a factor of a few of global efficiencies for individual compact clouds. Such efficiencies, when divided by δ yield pump efficiencies within the maser clouds themselves. For these parameters, implied efficiencies greatly exceed unity. Thus, a simple-minded assumption that the maser cloud extent is similar in 3 dimensions to the component sizes we observe in 2 dimensions leads to severe difficulties for infrared radiative pumping.

Possible Solutions. This calculation is based on spherical geometry and the assumption of isotropic radiation, from each observed parsec-scale maser spot. Normally, such geometries and assumptions are highly inappropriate for masers, because their nature as an exponential amplification process promotes highly directional radiation (into a solid angle Ω, the beaming angle), and elongated, cigar-shaped maser paths. Velocity-coherent linear paths through the masing medium produce an ensemble of different "cigars" in different directions and locations, of which we observe only a small fraction. For each spot, the total luminosity must be reduced by a factor $\Omega/4\pi$, and the surface area available to intercept IR pumping photons must be increased by the axial ratio of the "cigar". Competitive gain complicates such a picture, but the combination of these two factors can greatly ease apparent problems with pump energetics.

This mechanism for generating elongated masers with small Ω does *not* apply to the compact OH megamaser features, however. The broad velocity width of the spots implies that we are not picking out velocity-coherent paths pointed at us by chance, but instead are seeing lines of sight in which conditions for high maser gain are suitable for a wide range of velocities. Three possibilities are apparent for creating such lines of sight:

1. The most straightforward explanation is that the maser clouds are physically small in 3 dimensions, and are radiating roughly isotropically. This requires high volume emissivities, and challenges IR pumping schemes (see above).

2. The velocity field could be highly anisotropic, such that the velocity dispersion in one direction is much lower than in other directions. In such a situation, long gain paths are possible despite extreme apparent transverse velocity gradients. However, there is no obvious physical mechanism which could generate and maintain such velocity fields in a predominantly neutral medium, for several widely separated spots (for a single spot, orbital motions viewed from the plane of the disc might be a possibility). In addition, turbulence might be expected to quickly destroy such a highly ordered velocity field. This possibility will therefore not be explored further here.

3. The maser clouds could take the form of highly elongated, straight filaments with high internal velocity dispersion. This leads to a small effective Ω, but one based purely on the geometry of the inverted OH gas itself, not on the selection of long velocity-coherent gain paths. Gain paths are straight, but physical filaments are not required to be, so the observed spot compactness can place strong constraints on required filament geometries (straightness and transverse diameter) in this model.

Constraints and Implications The first possibility, physically compact clouds in 3 dimensions, can be accommodated in a few different ways. First, the IR pump source could be smaller and warmer than the one seen at far IR wavelengths. This decreases R in the geometry described above, and eases required IR pump efficiencies. Possibilities for such a compact IR source include a dusty torus around a nascent AGN (Lonsdale *et al.* 1994). The optical depths thought to exist in most luminous IR galaxies are consistent with such a small, warm IR source being hidden from view. Second, the compact masers may inhabit the innermost regions of these sources, where the optical depths at the wavelengths of the IR pumping lines are large. Pump photons may thus be effectively trapped, and cross the maser region many times, increasing the likelihood of hitting the cloud. Third, collisional pumping may play an important role in the inversion of OH molecules in the compact clouds. It is unlikely that the pump is purely collisional, based on the observed continuity of maser properties between the radiatively pumped diffuse masers and the compact masers. Nevertheless, the role of temperature, density, and possibly OH abundance enhancements behind shocks in the inner nucleus should be considered, and a collisional pump may become important under these conditions.

The third possibility, filamentary OH-bearing clouds of length l and diameter d, requires high axial ratios and filament straightness to fully explain the IR pump energetics. For the most extreme cases, required pump efficiencies must be reduced by a factor $(\frac{l}{d})^3$ of order 10^4, implying filaments with axial ratios l/d of order 20. The radius of curvature of such a filament must exceed a value of roughly $\frac{l^2}{2d}$, or of order 200 times the filament diameter (assumed to be comparable to the observed spot size), in order to generate structures compact in two dimensions instead of just one. This is a strong geometrical constraint. Filaments must also possess high internal velocity dispersions to explain the observed velocity widths, and must therefore be relatively short-lived physical structures (1pc/100 km/sec $\sim 10^4$yr).

Filamentary maser clouds may help explain the relationship between the compact and diffuse maser components (Elitzur, private communication). In this picture, the diffuse masers occur when radiation is weakly amplified in directions transverse to the filament orientation, naturally creating continuity of maser properties on a range of angular scales. It should be noted in this regard that in the only known instances of low gain amplification along specific, parsec-scale lines of sight, namely two amplified images of radio supernovae in Arp 220, narrow (few km/sec) line widths are observed. This has implications for the 3-D velocity field within the hypothetical filaments. Such a model also requires that the diffuse and compact masers occupy similar regions of the galaxy nucleus, rather than the compact masers being more deeply embedded.

A likely explanation for the compact masers is that a combination of possibilities 1 and 3 is operating. Compact, moderately elongated clouds with effective beaming angles substantially less than 4π, probably located in the innermost dense nuclear regions of sources with high FIR opacities, may be capable of producing the observed maser structures via radiative pumping alone. Much more observational data is required to further constrain such models, however.

3.3. Mergers, IR galaxies, AGNs and evolution

Many authors now postulate a well-defined evolutionary sequence associated with galaxy merger events (for a review see Sanders and Mirabel 1996). As two gas-rich galaxies collide, large-scale exchanges of angular momentum result in a significant fraction of the dust and gas settling into the center of the merging system, giving rise to extreme densities and dust opacities within the central few hundred parsecs. This dense environment fuels a burst of intense star formation, with extreme associated luminosity from young, high-mass stars, and a high rate of supernovae. The ultraviolet luminosity is reprocessed by dust into the far infrared, and the supernova remnants feed a bath of relativistic electrons which give rise to intense synchrotron radio emission from the nuclear region. Objects in this phase of the merger process are recognized as ultraluminous infrared galaxies.

The nuclear region is also a favorable environment for fuelling of accretion processes onto condensed objects. Pre-existing supermassive black holes in the nucleus of one or both merging galaxies are thought to ignite a phase of AGN activity, which is initially and very effectively hidden from view at most observing wavelengths by the large column densities of dust and gas in the nuclear regions. However, as the merger process continues, and as strong ionizing radiation from the buried AGN begins to dissipate the dense shroud, dust and dense molecular gas becomes confined to a torus, and eventually may be destroyed altogether. These phases correspond to a visible AGN phase, with appearance strongly dependent on torus orientation and viewing angle, eventually followed by a final quiescent elliptical galaxy phase during which the central black hole is starved for fuel.

While many questions remain concerning this evolutionary sequence, and many workers seek to confirm and refine, or refute, such a picture, it is reasonable to speculate about the OHM phenomenon in this context. The exclusive association of megamasers with luminous IR galaxies suggests that the strong heating and ionizing flux associated with visible AGN activity destroys the habitat of OH masers. The conditions for effective radiative pumping may be disrupted, or the OH molecules may be quickly dissociated. There are two lines of evidence which suggest that the compact masers may inhabit deeper, denser inner regions of the nucleus. First, some of the observed maser structures and velocity gradients are consistent with disks orbiting central masses, and may thus be direct probes of accretion and AGN genesis (e.g. Diamond *et al.* 1999). Second, and perhaps more compellingly, Mrk 231 displays no sign of compact masers in the innermost region, with diffuse masers being confined to a disk or torus structure some distance from the nucleus. This suggests that the visible, energetic AGN has heated and dissipated the dense molecular material close to the center, and has destroyed the habitat of the compact masers. The diffuse masers, which are postulated to live further out, have survived up to now, but presumably will succumb as the AGN continues to erode the dense ISM.

The hypothesis that compact masers lie deeper in the nucleus than the diffuse masers can be directly tested by appropriate imaging studies of a statistical sample of OHMs. An understanding of the relationship between diffuse and compact OHM components is crucial to their effective use as probes and diagnostics of the luminous IR galaxy phase, and possibly the earliest AGN ignition phase, of galaxy merger events.

4. OH megamasers at high redshift

The strong association of OHMs with luminous IR galaxies and the starburst activity presumed to power such objects raises the possibility of using OHMs as probes of galaxy merger and star formation activity in the distant universe. The empirical quadratic L_{OH}-L_{FIR} relationship, combined with the likely existence of extremely luminous high redshift systems, makes this a tantalizing possibility, emphasized by Baan (1989). More recently, Briggs (1998) has examined the detectability of high-redshift OHMs based on models of galaxy merger rate evolution. The conclusion was that the combination of strong merger rate evolution (at least as fast as $(1+z)^4$) and the OH luminosity dependence on FIR luminosity leads to a high probability of detectable OHMs in the redshift range 1-3, with modest integration times on current instruments.

Two issues may influence this conclusion. First, Kandalyan (1996) showed that the relationship between L_{OH} and L_{FIR} is not quadratic, but instead when corrected for Malmquist bias has an exponent closer to 1.3. Subsequent data from Darling and Giovannelli (2000; 2001) steepen the apparent relationship once more, but it should be noted that strong observational selection effects and many upper limits are present. The data require more rigorous statistical treatment, using the techniques of survival analysis and vigilance for hidden common dependencies.

Second, the distant galaxy merger population may differ markedly from the luminous IR galaxies studied in detail at lower redshift. During early epochs when galaxy building was less advanced, average masses of merging systems were smaller (see, e.g., Barkana and Loeb 2000), and the top end of the FIR luminosity function upon which OHM detectability most strongly depends may evolve very rapidly. High redshift OHM surveys may be a valuable diagnostic of such evolution.

5. Future Prospects

The direct study of OHMs is, to a large extent, sensitivity limited. Significant numbers of new OHM systems are being discovered only through the use of the 305-meter Arecibo telescope. VLBI imaging of the maser emission, capable of resolving detailed structure and velocity patterns, is possible for only a handful of the brightest objects in the sky. Because the masers are a narrowband phenomenon, current efforts to widen radio telescope bandwidths as a path to higher sensitivity (e.g. the EVLA project, and the wide-band MkIV VLBI system) offer limited prospects for improvement. Receivers at L-band are already close to theoretical performance limits. The only way to dramatically boost sensitivities for OHM and other line studies is thus to employ more physical collecting area, the principal goal of the Square Kilometer Array (SKA) project. The capabilities of the SKA in this respect are nothing short of spectacular, placing tens of thousands of OHM sources into a high-snr category for which detailed study is possible. This project, however, is unlikely to reach fruition until well into the next decade.

It should be noted that global VLBI fails to fully resolve the emission. This problem can be solved only by space-based VLBI, but unfortunately the necessary space-VLBI sensitivity is unlikely to materialize this decade, or possibly much later.

In the interim, several interesting observational lines of attack on the OHM phenomenon are possible. Incremental improvements in sensitivity will occur, particularly for VLBI as new telescopes such as the GBT, and major European instruments, come on line. Modest benefit can be obtained from increased VLBI bandwidths, in the form of multibit sampling and oversampling, thereby minimizing digital losses. Advanced recording and data transport techniques may permit better recording duty-cycles and longer effective integration times for VLBI. Improving RFI mitigation techniques may ease the task of studying OH line sources that have been redshifted out of protected radio astronomy bands, and permit the detection and characterization of distant OH gigamasers. Improving VLBI capabilities in the southern hemisphere should open several strong southern sources to detailed study. Improvements to MERLIN, the European VLBI network (EVN), and the resolution enhancement of EVLA phase II should gradually boost our capability to image intermediate scales of emission over the coming 5 to 10 years. Monitoring programs can characterize OHM variability. Excited-state OH transitions, and far-IR pump-related lines can both be studied, the latter in detail with SIRTF.

Together, these opportunities provide the potential for steady progress in the study of OHMs, and the broader topics informed by such studies.

6. Conclusions

In recent years, the study of OHMs has yielded surprises, and valuable insights into the hidden interiors of merging galaxy systems. The physical nature of the masers remains in question, particularly with regard to the more compact features, and additional theoretical work is warranted. Observationally, constraints of limited sensitivity and angular resolution are not easily overcome. However, considerable scope remains for progress in the near future, and in the next decade, major new instrumental capabilities will revolutionize the study of OHMs, and powerfully complement the wealth of information on galaxy merger systems to be generated by ALMA.

It seems clear that the masers trace important and energetic phenomena within the highly obscured central regions of these powerful IR galaxies, objects which result from a galaxy merger process of profound cosmological significance. Possibilities include shocks associated with nuclear starbursts and superwind genesis, and the birth of AGN activity. The dust-penetrating character and parsec-scale structure of OHM emission may eventually prove to be essential ingredients in the quest to understand the evolution of galaxy merger events.

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