Megamasers

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Abstract The two decades following the serendipitous discovery of megamasers have seen tremendous progress in the study of luminous extragalactic maser sources. Single-dish monitoring and high resolution interferometry has been used to elucidate physical parameters of the nuclear starbursts triggered by spiral galaxy mergers and to constrain properties of circumnuclear accretion disks, including the degree of warping, density, temperature, magnetic field, disk stability, mass acccretion rate, and mass of the nuclear engine. To date, ∼100 OH megamasers and ∼25 H_2O megamasers have been detected, but only few have been studied in detail.

1 Introduction

In the thirty years since their discovery, the study of cosmic masers has been an exciting and rapidly growing area of research. Most galactic OH and H_2O masers are the size of our solar system or smaller and thus require Very Long Baseline (VLB) techniques to be resolved. Extragalactic masers are rarely resolved, but can efficiently be used as signposts of massive star formation and active galactic nuclei (AGN). Because their luminosity can be truly outstanding, reaching $10^4\,L_\odot$ (10^{54} photons/s) in the most extreme cases, they are observed out to large distances.

To date, five molecular species have been observed as masers in extragalactic space: SiO, CH, H_2CO, OH, and H_2O. The SiO J=2–1, v=1 maser (86 GHz), detected in the Large Magellanic Cloud (LMC; van Loon et al. 1996), appears to be similar to those observed in the circumstellar shells of galactic giant stars. CH (3264 MHz) emission was reported towards the LMC, NGC 4945, and NGC 5128 (Cen A) and CH (3335 MHz) emission was measured towards the LMC (Whiteoak et al. 1980). These lines behave like weak masers towards most galactic clouds (e.g. Hjalmarson et al. 1977) and it is therefore not farfetched to assume that the extragalactic lines are also caused by weak unsaturated maser emission. The first extragalactic H_2CO maser (4829 MHz) was discovered by Baan et al. (1986) in Arp 220. They proposed a pumping scheme based on infrared photons from the dust and seed emission from radio photons from the nuclear continuum source(s). Such 6 cm H_2CO masers are rare in the Galaxy. They appear to be linked to OH megamasers (e.g. Henkel et al. 1991; Baan et al. 1993), possibly because infrared radiation plays a role in pumping both maser types. For Arp 220, a detailed comparison of interferometric maps of OH, H_2CO, and the radio continuum is given by Baan & Haschick (1995). The main focus of astrophysical research is not on SiO, CH or H_2CO, however, but on extragalactic OH and H_2O masers. Studies of these molecules provide insights into astrophysical problems and processes that are otherwise difficult to discern. A few highlights are presented in the following sections.

2 OH Emission

Interstellar OH maser emission, initially dubbed 'mysterium' because of its peculiar line profile, was first detected by Weaver et al. (1965) and Gundermann (1965) towards galactic star forming regions. Extragalactic OH masers were observed by Whiteoak & Gardner (1973, 1975), in the starburst galaxies NGC 253 and NGC 4945. These are the first (comparatively weak) known 'kilomasers'. The first OH 'megamaser', with a luminosity surpassing any galactic OH maser by orders of magnitude, was detected by Baan et al. (1982) in the ultraluminous starburst galaxy Arp 220. Line emission was measured in the 'main lines' of the ground state Λ-doublet (1665 and 1667 MHz). With the launch of the Infrared Astronomical Satellite (IRAS) providing 12–100μm fluxes of many galaxies, it soon became clear that OH megamasers are closely associated with Ultraluminous Infrared Galaxies (ULIRGs), i.e. with merging gas-rich spirals. At luminosities of $10^{12}\,L_\odot$ every second (Baan 1989) or third (Darling & Giovanelli 2002a) ULIRG exhibits strong OH emission. Assuming that every such system contains a megamaser but some are not detected because of beaming and orientation effects, a lower limit to the solid angle of the coherent radiation can thus be determined.

Guided by the IRAS Point Source Catalog (e.g. IRAS 1989), ∼50 megamasers were detected within a few years. Towards Arp 220, not only the main lines but also the satellite lines of the ground state Λ-doublet (1612 and 1720 MHz) were found in (weak) emission (Baan & Haschick 1987), while a total of five lines from higher excited Λ-doublets (the $^2\Pi_{1/2}$, J=1/2 4660, 4751, and 4766 MHz transitions and the $^2\Pi_{3/2}$, J=3/2 6030 and 6035 MHz transitions) were observed in absorption against the nuclear continuum (Henkel et al. 1986, 1987).

The detection of a number of lines and the availability of a large number of infrared photons strongly constrain any pumping scenario. Excitation by infrared emission was thus proposed early (Baan 1985; Norris et al. 1995) and supportive numerical calculations were performed by Henkel et al. (1987), Burdyuzha & Vikulov (1990), and Randell et al. (1995). Further confirmation was obtained by the detection of strong 35μm OH absorption (Skinner et al. 1997) that alone is capable of pumping the megamaser emission seen at radio wavelengths. Nevertheless, more accurate calculations exploring the full parameter space would be highly desirable.

The standard OH megamaser model involves unsaturated maser emission amplifying the nuclear continuum background (Baan 1985; Henkel & Wilson 1990). More recent VLBI studies of Arp 220 (Lonsdale et al. 1994, 1998) reveal that the 1665 MHz flux and a part of the 1667 MHz flux is resolved out, apparently arising from extended sources with a low maser gain that may be compatible with the standard model. However, the remaining 1667 MHz flux has high gain and arises from possibly saturated maser emission in compact clouds. Such compact emission regions may be responsible for time variability observed in IRAS 21272+2514 (Darling & Giovanelli 2002b). High resolution maps of other sources provide an even more complex picture (see Montgomery & Cohen 1992; Trotter et al. 1997; Diamond et al. 1999; Yates et al. 2000; Pihlström et al. 2001). Overall, OH and infrared luminosities are correlated, with $L_{\rm OH} \propto L_{\rm FIR}^{\beta}$. Originally, β was believed to be ∼2 (Baan 1989), which corresponds to unsaturated emission ($L_{\rm OH} \propto L_{\rm c}\,L_{\rm FIR}$ with $L_{\rm c}{\propto}L_{\rm FIR}$ and $L_{\rm c}$ denoting the radio continuum luminosity). However, more recent studies give $\beta = 1.38$ (Kandalyan 1998) and 1.2 (Darling & Giovanelli 2002a). It may be that the detection of particularly distant and luminous OH megamasers has significantly decreased the fraction of sources with unsaturated emission, thus also reducing β.

3 H_2O masers

In contrast to OH, extragalactic water vapor (H_2O) masers, first detected by Churchwell et al. (1977), have so far been observed in only one line. Therefore pumping scenarios are not well constrained. Nevertheless, collisional excitation at densities 10^8–10^{10} cm^{-3} and temperatures of ∼250–500 K appear to be adequate to produce such masers (e.g. Elitzur 1998). The rotational energy states connected by the highly time variable 22 GHz line are high enough (∼640 K) above the ground level not to be strongly affected by atmospheric extinction. As in the case of OH, there are comparatively weak kilomasers (up to a few solar (isotropic) luminosities) that can be used to pinpoint sites of massive star formation and to obtain distance estimates by a comparison of the scatter in radial velocity and proper motion (e.g. Greenhill et al. 1993; Tarchi et al. 2002). Proper motions can also be used to obtain three dimensional velocity vectors in the Local Group (Brunthaler et al. 2002). Only one kilomaser is known to be associated with the nuclear environment of a galaxy. It is observed toward the Whirlpool galaxy M 51 (Hagiwara et al. 2001).

Megamaser emission exceeding ∼20 $L_\odot$ was first observed towards NGC 4945 (Dos Santos & Lépine 1979) and then in four additional sources (Gardner & Whiteoak 1982; Claussen et al. 1984; Henkel et al. 1984; Haschick & Baan 1985). Claussen and Lo (1986) associated the maser emission with the active nucleus, but it took some 10 years until additional progress was made in our understanding of extragalactic H_2O sources. A large survey including ∼360 Seyfert and LINER galaxies (Braatz et al. 1994, 1996, 1997) led to 10 new detections, all of them associated with galaxies containing a Seyfert 2 or LINER nucleus. This result and continuing interferometric observations reinforced the nuclear origin. The emission originates from the innermost parsec(s) of the parent galaxy (e.g. Claussen & Lo 1986; Greenhill et al. 1995b; 1996, 1997b; Miyoshi et al. 1995; Claussen et al. 1998; Trotter et al. 1998; Herrnstein et al. 1999; Peck et al. 2001). Adopting a so-called unified model in which Seyfert 2 nuclear disks are viewed edge-on, megamaser activity must then be related to the large line-of-sight column densities available only in edge-on orientations.

To date, the number of known H_2O megamasers surpasses 20 (for more recent detections, see Koekemoer et al. 1995; Greenhill et al. 1997a, 2002; Hagiwara et al. 1997, 2002a; Falcke et al. 2000; Henkel et al. 2002). The H_2O line provides the only opportunity to map accretion disks in AGN. It also permits the determination of the mass of the supermassive nuclear object, to obtain direct geometric distances to galaxies, and to study the interaction between nuclear jets and dense molecular material. The masers appear to divide into a few classes: those found in nuclear disks, those originating along powerful radio jets, and those which are neither associated with disks or jets. Among the so-called 'jet masers', NGC 1052 (Claussen et al. 1998) and Mrk348 (Peck et al. 2001) are the most prominent. The prototypical source of the third class is NGC 3079 (e.g. Hagiwara et al. 2002b).

Most interesting are the circumnuclear 'disk-masers', with NGC 4258 being the prototype. VLBI observations (Greenhill et al. 1995b; Miyoshi et al. 1995; Herrnstein et al. 1999) provide strong support for the presence of a thin (height to radius ratio $< 0.3\%$; Moran 1998), warped, almost edge-on gaseous disk or annulus at a galactocentric radius of 0.16–0.28 pc. Maser emission is observed both within 100 km s^{-1} of the systemic velocity, arising from the clouds on the near side of the disk and along our line of sight to the central core, and from 'satellite lines' with velocities ± 900 km s^{-1} w.r.t. systemic velocity (Nakai et al. 1993), arising from gas at the tangent points, with rotational velocities directed towards and away from Earth. Haschick et al. (1994), Greenhill et al. (1995a), and Nakai et al. (1995) monitored the maser spectrum and found that the systemic maser features drift redward with time at a rate ∼9 km s^{-1}. These velocity drifts are interpreted as centripetal acceleration (V^2/R) of clouds in the rotating disk as they orbit the central black hole. Systemic maser features may only be seen when gas is projected in front of the innermost part of the southern jet, which the masers likely amplify. Satellite lines are believed to be self-amplified. The Keplerian disk requires a binding mass of $(39\pm1)\times10^6$ (D/7.2 Mpc) (sin i/sin 82°)$^{-2}$ $M_\odot$ inside of 0.16 pc.

In NGC 4258 the centripetal acceleration, V^2/R, is known from velocity drifts and the velocity of rotation, V, is known from the satellite emission lines. Thus the linear radius, R, is known and can be compared to the VLBI-measured angular size of the disk, θ, to give the distance to the source, $D = R/\theta$. This calculation can be further tested by directly measuring the proper motion of the systemic maser components as they pass the inner edge of the disk along the line of sight towards the innermost southern jet (Herrnstein et al. 1997, 1999). The result is $D = 7.2\pm0.5$ Mpc. The original distance estimate obtained from Cepheids (Maoz et al. 1999) was discrepant with the distance obtained from the maser measurements, but a reevaluation of the Cepheid calibration schemes gives $D = 7.8\pm0.3\pm0.5$ Mpc (Newman et al. 2001), consistent with the maser distance.

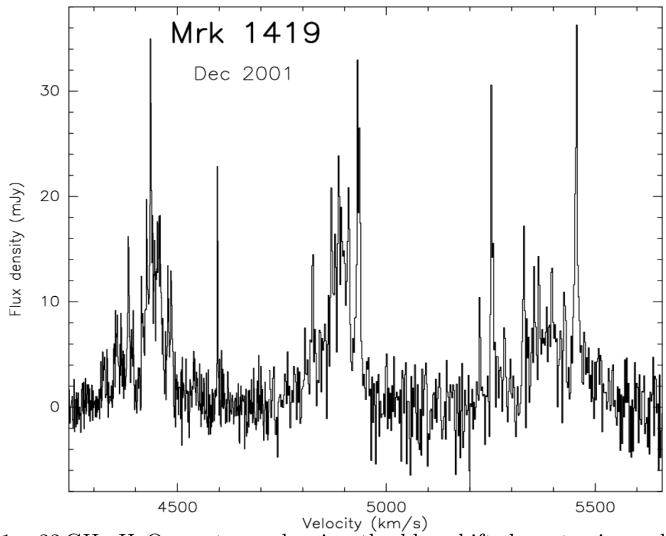

Fig. 1 22 GHz H_2O spectrum showing the blue-shifted, systemic, and red-shifted maser features (Henkel, Braatz, Greenhill & Wilson 2002).

Among the newly detected objects, one megamaser shows the same properties as the prototypical accretion disk maser source NGC 4258 (Henkel et al. 2002): The spectrum is characterized by a cluster of systemic ($V\sim V_{\rm sys}$) H_2O features, two additional H_2O clusters, one red- and one blue-shifted with respect to $V_{\rm sys}$, a likely acceleration of the systemic features and no similar drift in the blue- and red-shifted emission. The source has a recessional velocity ten times that of NGC 4258 (see Fig. 1).

4 Future prospects

With the completion of the GBT (Green Bank Telescope), the E-VLA, and the recently improved system at the Effelsberg 100-m telescope, new H_2O masers will be found. Hopefully, some of these will also reveal a clear disk geometry as observed in NGC 4258, so that more nuclear masses and geometric distances can be estimated. By including these highly sensitive telescopes in VLB arrays, it will be possible to obtain interferometric observations of the distant, weaker masers which is essential to detailing their geometries and obtaining distances. Finally, one H_2O megamaser host galaxy has been recently identified as a Narrow Line Seyfert 1 (Nagar et al. 2002) and two new megamasers were recently detected in luminous galaxy mergers (Hagiwara et al. 2002a; Peck et al. 2003). Thus the commonly adopted exclusive association of H_2O megamaser emission with Seyfert 2 and LINER nuclei may have to be modified.

OH and H_2O megamasers alike may be suitable tools to determine magnetic field strengths (the component parallel to the line-of-sight) through observations of Zeeman line splitting in circumnuclear disks and regions close to merging galactic nuclei. So far, only upper limits could be obtained. For OH in four sources including III Zw 35, 3σ values for the magnetic field strength are 3–5 mG (Killeen et al. 1996) and for the circumnuclear H_2O emission in NGC 4258 it is 900 mG (Herrnstein et al. 1998).

About 100 OH megamasers have been detected so far, half of them at redshifts z=0.1–0.3 (Darling & Giovanellli 2002a). Although OH megamaser emission appears to be a starburst- and not an AGN-phenomenon (e.g. Sturm et al. 1996), it may soon become, as in the eighties, the main focus of astrophysical megamaser research. This is a consequence of their enormous luminosities which make them detectable at cosmologically interesting distances, and their association with ULIRGs (e.g. Baan 1989; Darling & Giovanelli 2002a). With the Arecibo telescope, the most luminous known OH masers would be detectable out to $z\sim0.7$. With the GMRT (Giant Meter Wave Radio Telescope) and LOFAR (Low Frequency Array), the most luminous sources should be detectable out to redshifts of $z\sim6$, while the construction of an SKA (Square Kilometer Array) would provide direct access to weaker OH megamasers as well, throughout the universe. Assuming that OH emission is closely related to the presence of ULIRGs, not only 'locally' but also at high redshifts, the number of detected masers as a function of redshift will then provide a direct estimate of the number of merging spirals and star formation rate as a function of time. This could be compared with other interesting populations like that of quasars to study the evolutionary connection between the ULIRGs and QSOs (e.g. Sanders 1996).

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