MEGAMASERS IN ACTIVE GALACTIC NUCLEI

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1. Introduction

Extragalactic masers were discovered more than 20 years ago (Whiteoak & Gardner 1973). It soon became apparent that those extragalactic masers we can detect are intrinsically very powerful and are located in galactic nuclei. The term Megamaser was coined to describe the most luminous OH masers, which are a million times more powerful than any OH masers within our own Galaxy (Baan & Haschick 1984). The same word is nowadays applied to any powerful maser associated with an active galactic nucleus (AGN). Whereas normal Galactic masers would be barely detectable outside the Local Group, megamasers are detectable in principle out to redshifts of $z \sim 2$ (Baan 1997). The galaxies hosting megamasers in their nuclei are invariably active in some degree: they include ultraluminous infrared galaxies, starbursts and Seyfert galaxies.

Masers occur in a wide variety of environments in the Galaxy, from comets and circumstellar envelopes to star-forming regions. Molecular masers amplify the natural line emission or a continuum background, along paths where there is frequency resonance or velocity-coherence. The requirement for a long amplification path in a megamaser provides a natural link with the optical appearance of the associated galaxy. Maser emission from a molecular torus or disk surrounding an AGN will be beamed in the plane of the disc, where the amplification path is longest. Thus the disc orientation relative to our line-of-sight will influence both the detectability of the maser emission and the optical appearance of the galaxy. We expect the strongest megamasers to be those where the nucleus is most heavily obscured.

Maser emission is a powerful tool for probing AGN. The compact masers can be mapped and positioned with milliarcsec precision, enabling us to locate the hidden nucleus and measure proper motions in the orbiting gas clouds. Maser variability gives us size estimates, timescales and sometimes phase-lags, all of which can lead to distance estimates, particularly when combined with proper motion measurements. Masers also give us information about the magnetic field strength through the Zeeman effect, and about the physical conditions through the pumping requirements of each maser transition.

Of the many different maser molecules only four have been detected in external galaxies: OH, H_2O, H_2CO and CH. This review will concentrate on the first three species, where there have been spectacular developments in imaging the megamasers. The situation for CH is essentially unchanged since the review by Henkel, Baan & Mauersberger (1993). Before beginning my review I would like to point out that many of the exciting recent developments were foreshadowed ten years ago. Stavely-Smith et al. (1987) first detected high-velocity OH emission from Mkn231 and Mkn273, at velocities approaching 1000 km s^{-1} which could only be associated with the Seyfert nuclei of these galaxies. Even more prophetically, Claussen & Lo (1986) measured correlated variability in nuclear H_2O masers, from which they inferred length scales of 1 pc for NGC1068 and 0.1 pc for NGC4258, which have since been measured directly using VLBI, as described below.

2. OH Megamasers

The prototype OH megamaser Arp220 (IC4553) was found almost by accident by Baan, Wood & Haschick (1982) who were searching for OH absorption. It proved very hard work to find more megamasers until the IRAS catalogue was published in 1985. Then it became clear that the megamaser galaxies are ultraluminous infrared galaxies. Search programmes based on the IRAS catalogue were

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an immediate success (provided the redshift did not place the OH lines too close to the frequencies used by the GLONASS and GPS navigation satellites). There are now some 60 OH megamasers known. They radiate primarily in the red-shifted 1665- and 1667-MHz mainlines, with the 1667-MHz line generally strongest, and with luminosities up to $\sim 10^{30}$W.

The OH megamaser galaxies have disturbed optical morphologies due to strong interaction or merging of gas-rich systems (Sanders & Mirabel 1996). One consequence of the interaction is to funnel a large amount of molecular gas into the nuclear region. Arp220 for example has more CO in its nucleus than most galaxies have altogether (Scoville et al. 1986, and this conference). As a result the megamaser nuclei are heavily obscured. The optical spectra show either LINER or Seyfert2 characteristics. The enormous infrared luminosity is thought to be powered by either a circumnuclear starburst or an AGN, or some combination of both. For example Mkn273 has three radio sources and two infrared sources in its nucleus, which are attributed to an AGN and a distributed starburst (Knappen et al. 1997).

The OH megamaser emission itself generally comes from an extended region $\sim$100 pc in size. When mapped at high angular resolution with MERLIN or the VLA the emission shows a systematic velocity gradient consistent with a rotating molecular disk or torus (Montgomery & Cohen 1992, and references therein). At the higher resolution achieved by VLBI, it is found that about half the OH emission comes from compact components $\sim$10 pc in size (Lonsdale et al. 1994; Trotter et al. 1997). In the case of IIIZw35 the compact components themselves show velocity gradients at a different position angle, but neither of the megamaser position angles agrees with the optical morphology of the interacting pair of galaxies. It is often claimed that OH megamasers amplify the radio continuum radiation from the AGN. However no published VLBI measurements have yet revealed a compact radio continuum nucleus directly behind a compact OH megamaser component. Thus we can set only lower limits to the gain of the maser, at the present time.

OH megamasers may one day provide direct measurements of the magnetic field strength in AGN. Killeen et al. (1996) have attempted to measure the Zeeman effect in IIIZw35 and in three strong southern megamasers, using the Australia Telescope Compact Array. Their data imply upper limits to the magnetic field strength of 3 – 5 mG, depending on the assumptions made about the field configuration.

Recent ISO measurments of the prototype OH megamaser source Arp220 have gone a long way towards establishing the nature of the nuclear source and the physics of the megamaser emission. Pairs of infrared lines which are well separated in wavelength, such as Brα and Brβ, or [SIII] at 18.7 and 33.5 microns, can be used to measure the extinction to the nucleus. The ISO data give an extinction of A_V $\sim$50 mag, significantly higher than most previous estimates (Sturm et al. 1996). Pairs of lines of the same species in different ionization states and which are close in wavelength, such as [NeII] and [NeV] near 14 microns, can be used to measure the excitation. High excitation lines such as [NeV] and [OIV] are absent from the ISO spectrum of Arp220, although they are prominent in the spectra of active galaxies such as Circinus (Moorwood et al. 1996). This indicates that any central AGN in Arp220 can be only a minor contributor to the total infrared luminosity (Sturm et al. 1996). Thus although we see OH megamasers in Seyfert-2 galaxies such as Mkn231 and Mkn273, an AGN does not seem to be an essential ingredient for OH megamaser emission.

It has long been suspected that the infrared radiation field in megamaser galaxies must pump the megamaser. Direct confirmation has now come from the ISO observations by Skinner et al. (1997). They detected strong absorption in the 35 micron line of OH which would be sufficient on its own to pump the megamaser. The 53 micron line is also expected to contribute to the excitation of the OH, and further ISO observations to detect this line and others associated with the radiative cascade are in progress. The strength of the 35 micron absorption indicates that the region emitting the pumping radiation must be very extended, which points to a distributed starburst rather than a single AGN at the centre (as deduced independently by Sturm et al.). From these examples it is clear that ISO has a major role to play in future investigations of OH megamasers.

3. H_2CO Megamasers

Formaldehyde megamasers are true megamasers, in that they are one million times more powerful than Galactic H_2CO masers. Nevertheless they are rather weak radio sources, with peak flux densities of only a few mJy, so they have not received much attention. About ten sources are known

(Baan, Haschick & Uglesich 1993). They are associated with OH megamaser emission or OH absorption, and generally cover a similar velocity range to the OH. Both the 4.8- and the 14.5-GHz transitions of H_2CO have been detected.

Only one H_2CO megamaser has been mapped at 4.8 GHz: Arp220 (Baan & Haschick 1995). As for OH, the H_2CO megamaser emission comes from two distinct regions associated with the double continuum nucleus. The H_2CO peaks are systematically displaced from the continuum and OH peaks. This is interpreted by Baan & Haschick as evidence for orbital motion of the two nuclei at $\sim$200 km s^{-1}, with the OH leading the continuum components and the H_2CO slightly trailing.

4. Nuclear H_2O Masers

Extragalactic H_2O masers appear to be of two types: normal Galactic-type H_2O 22-GHz masers found mainly in the spiral arms of nearby galaxies, and more powerful 22-GHz masers found in AGN. This latter group are mega in the sense of being very interesting or sexy, but in terms of their luminosity they are mere kilomasers, 10 – 1000 times Galactic. The prototype is NGC4258. About 20 sources are presently known, and the number is increasing slowly.

Only the 22-GHz transition of H_2O has been detected to date. It is worth remarking however that strong mm- and submm H_2O maser transitions occur in star-forming regions and circumstellar envelopes within the Galaxy. They might also be expected to occur in AGN, where the redshift would move the line out of the Earth's atmospheric H_2O absorption and so make detection easier.

Searches for nuclear H_2O masers have concentrated on the very same sources that were originally searched for OH megamasers, with similar low success rates. The most extensive survey yet, by Braatz, Wilson & Henkel (1996), yielded 10 new detections from 354 galaxies. The low detection rate may reflect the small area of sky into which the maser emission is beamed. There appears to be no clear infrared signature for nuclear H_2O masers. They are detected only in Seyfert2 and LINER galaxies, and never in OH megamaser galaxies (Braatz et al. 1997). It seems likely that any H_2O masers in Seyfert 1 nuclei would be beamed away from Earth and so escape detection.

The nuclear H_2O masers are intrinsically very different from OH megamsers. They are much more compact, with characteristic sizes of 1 pc or less, they vary in intensity on timescales of a month, and they exhibit long-term drifts in the velocities of the individual emission peaks. The host galaxies do not have the massive concentrations of molecular gas on the kiloparsec scale which are a feature of the OH megamaser galaxies. In fact the whole phenomenon of the nuclear H_2O masers seems to be dominated by the compact massive object in the AGN. What we have is a small dense molecular torus around the AGN, seen edge-on, and with a clear rotational signature which is seen in the velocity drifts and in VLBI maps.

The prototype NGC4258 is one of the strongest extragalactic H_2O masers known. The host galaxy was long suspected to house an AGN on account of its anomalous Hα and radio continuum arms, which appear to have been ejected from the nucleus in a N-S direction (van der Kruit, Oort & Mathewson 1972). The H_2O maser attracted attention firstly because of its variability (Claussen & Lo 1986), and secondly because of its extremely high velocity emission features, which were discovered using a bank of 8 spectrometers at Nobeyama (Nakai, Inoue & Miyoshi 1993). The extreme velocity peaks occur 900 km s^{-1} above and below the systematic velocity of the galaxy. Systematic monitoring of the bright central emission by Haschick, Baan & Peng (1994) revealed that all the features are systematically drifting in velocity. This was interpreted as acceleration in circular orbits about a massive nucleus.

Watson & Wallin (1994) were able to construct a theoretical model which explained many features of the observations in terms of a thin rapidly rotating disk seen edge-on. The disk configuration is ideal for maser action because it achieves long path lengths through the disk while allowing infrared photons to escape perpendicular to the disk. The kinematics of the edge-on disk give rise naturally to high velocity emission features at the extremes of radial velocity, where the velocity coherent paths are longest. In order to achieve bright emission in the centre of the line profile it was necessary to assume that the H_2O masers amplify a central radio continuum source. Individual clouds then appear in maser emission as their orbits carry them in front of the continuum source, and at the same time their radial velocity drifts due to the orbital acceleration.

The picture just described was spectacularly confirmed by the VLBA observations of Miyoshi et al. (1995), published in what was surely the most exciting maser paper for many years. The VLBI maps show three separate concentrations of masers in a thin E-W distribution. The extreme blue- and red-shifted emission features occur on each side of the bright central emission features, with velocity gradients exactly consistent with Keplerian rotation. The bright central emission shows a velocity gradient in the opposite sense which exactly matches the signature for circular rotation. Using the accurately measured parameters of the disk and the precise velocity drifts measured by Haschick et al. (1994), Miyoshi et al. were able to calculate an accurate distance to NGC4258 and hence determine the linear size of the disc and the mass of the AGN. They were also able to predict the size of proper motions of the individual maser clouds in front of the nucleus, which have now been directly measured (Moran, this conference).

Fortunately for us NGC4258 is not the only example of this phenomenon. The nuclear H_2O masers in NGC1068 have already been confirmed to have a rapidly rotating thin disc configuration (Gallimore et al. 1996; Greenhill et al. 1996) and systematic velocity drifts have been measured in this source and in NGC3079 (Baan & Haschick 1996). For these and other sources which are beamed towards us, the H_2O masers offer a powerful tool for investigating the central regions of active galactic nuclei.

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