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Astrophysical masers

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A brief introduction to the concept of a natural maser is followed by a history of the discovery of masers in space and a discussion of their basic properties. Several arguments are put forward that effectively exclude the possibility of such bright, compact radio sources arising from any other radiation process. The present state of observational knowledge is reviewed with reference to various source regions: massive star-forming regions; circumstellar envelopes; cores of external galaxies (megamasers); supernova remnants; comets; and planetary atmospheres. A complementary review of maser theory discusses progress on the understanding of the saturation, polarization and beaming of astrophysical masers, and the need for accurate molecular data, such as collisional rate coefficients. Likely future opportunities are discussed both for observations and theory. New instruments, some space based, and improved detector technology will revolutionize maser observations, while improved computing power will allow ever more sophisticated modelling. Various applications of masers as astrophysical tools are considered, with applications to distance measurement, cosmology and the SETI programme.

Keywords: masers; radio lines; molecules

1. Introduction

Molecules in a gas typically have many internal energy levels due to various modes of motion, including vibration, rotation and more subtle effects such as nuclear spin. Usually, we expect these levels to be populated such that if we compare the number of molecules in two of these levels, the number of molecules in the higher level will be the smaller. Under exceptional conditions, however, the reverse can be true, and a population inversion is then said to exist between the two levels. A population inversion is a prerequisite for maser action. The energy difference between the two levels will correspond to some photon frequency, and, provided the transition between the levels is allowed according to quantum selection rules, the transition will be capable of forming a spectral line at this frequency. A photon interacting with a molecule in the lower state undergoes absorption and is lost, promoting the molecule to the upper state; if the molecule is in the upper state, stimulated emission occurs, with the photon copying itself while the molecule descends to the lower state. Obviously, the latter process increases the number of photons, while the former reduces it. If we have a population inversion, the stimulated emission will dominate over absorption, and the number of photons will amplify by stimulated emission, producing a natural maser (microwave amplification by stimulated emission of radiation). Natural

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masers have much in common with laboratory masers and lasers (lasers use optical light rather than microwave frequencies) but lack the mirrored cavity that gives laboratory instruments their very precise beam and frequency characteristics.

It is only 35 years since the first astrophysical maser was detected (Weaver *et al.* 1965). Initially, the source caused consternation and the substance responsible was dubbed 'mysterium'. Very quickly, the spectral line was identified as a transition of the OH (hydroxyl) molecule (Weinreb *et al.* 1965), and an explanation of the signal was provided in terms of amplification by stimulated emission of radiation: a natural maser, or microwave laser (Davies *et al.* 1967).

The main problem in identifying the original maser line was that it is intrinsically very weak, and, therefore, not expected to be observable. One great advantage of maser sources is, thus, immediately apparent: the amplification process allows us to view small regions and weak transitions that we can observe by no other means. Astrophysical maser sources are so small that they usually have to be measured by an aperture synthesis interferometer, an array of telescopes operated together to boost the angular resolution by the factor of roughly the telescope separation to the diameter of an individual dish. The first measurements of this type on masers were performed by Reid *et al.* (1980) Individual spots of emission can have angular sizes of 1 mas (milliarc second) or less, which at typical source distances within our Galaxy converts to linear sizes of a few AU, where 1 AU (astronomical unit), is equal to the mean Earth–Sun separation, or 1.5×10^{11} m.

The development of the subject up till about 1990 has been well reviewed by Cohen (1989) and by Elitzur (1992). Basically, progress has followed three main avenues. The first is the discovery of more maser transitions in more astrophysical molecules. A current list of astrophysical maser molecules comprises OH, H_2O, SiO, CH_3OH, NH_3, H_2CO (formaldehyde or methanal), HCN, SiS, CO_2, CH, H. These range from Rydberg states of the simple hydrogen atom to CH_3OH (methanol), one of the more complex molecules found in the interstellar medium. There is no reason to suppose that this list is complete, and other molecules may well be found to emit maser radiation in the future: maser emission has been predicted from molecular oxygen for example (Bergman 1995). Typically, each molecule produces maser emission from more than one of its transitions, so the number of maser lines, or frequencies, which have been detected outnumbers the list of molecules many times. A second field of growth is in source type. The original detection was in a region of star formation inside our own Galaxy. Astrophysical masers have also been detected in association with the circumstellar envelopes of highly evolved stars, supernova remnants, comets in our own solar system, and with the atmospheres and magnetospheres of planets. A much more energetic type of source, the so-called 'megamaser' systems (Baan *et al.* 1982), has been observed from the active cores of certain external galaxies. The name derives from the fact that these sources are, typically, a million times brighter than the maser sources in our Galaxy. Other masers do not originate from molecular transitions at all, but are derived from the free-electron maser process in plasmas and can be observed, for example, in solar flares and have been suggested as the origin of the core emission from pulsars. Thirdly, there has been a theoretical and computational effort to back up the observations and attempt to understand the astrophysical maser phenomenon. Only by understanding the way that masers are pumped and the way in which they amplify, beam and saturate can we begin to make use of these objects as tools that can be used to give useful information about their environments. By and large, the theoretical effort has not kept up with the observational techniques, but, nonetheless, considerable progress has been made towards an understanding of these spectacular radio sources.

2. General characteristics

How do we identify a source as a maser? It is best to start by assuming that a source arises from a thermal process, and proceed to show that this initial assumption cannot be correct. Define the brightness temperature of the source as the temperature it would have to have as a black body in order to give the observed specific intensity. The specific intensity is usually measured in units of Jy sr^{-1} or Jy per telescope beam, where 1 Jy (Jansky) is a radio astronomers' flux density unit, equal to $10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$. If the initial assumption is valid, the calculated source temperature must be lower than the highest temperature for which the molecule concerned can exist, in the range of a few hundred to a few thousand kelvins. For maser sources, the calculated temperatures, depending on the molecule and source type, range from a modest 10^4 K to over 10^{14} K, many times hotter than the core of the Sun. Clearly, such temperatures are not consistent with the existence of molecules and we reject the initial assumption in favour of the idea that these sources are masers, amplified by stimulated emission of radiation. Although this argument is very strong evidence in favour of a maser explanation of these sources, actual proof requires additional evidence relating to coherence properties of the radiation, which will be discussed later.

Radio astronomers usually convert the observed frequencies of spectral lines to velocities via the Doppler effect, and linewidths can be treated similarly. The maser line profiles are Doppler broadened: their widths reflect the thermal motions, or the temperature, of their molecules, but with some narrowing due to the amplification process. Narrow components in a spectrum, with a sub-thermal width, are, therefore, also pointers to maser emission, as are strong polarization and peculiar ratios of line flux densities, but these arguments are all secondary to that given above.

When observing stars and planets, the spherical geometry of these objects is an enormous aid in the interpretation of the observations. By contrast, masers have no well-defined geometry: interferometer maps reveal objects of irregular shape, which makes them both intriguing and challenging. This problem is compounded by the fact that, unlike a star, the maser's radiation pattern could be very different from its physical geometry. A roughly spherical clump of gas, for example, could give rise to a highly beamed maser, with a very small opening angle.

If we have maser emission, there must be a population inversion in the source, so that light amplifies through it. Maintenance of the inversion requires a pumping mechanism. Three types of mechanism can contribute to the overall pump: collisions with partner atoms and molecules, which, in astrophysics, usually means a mixture of atomic and molecular hydrogen plus helium; radiation, usually of far-infrared (FIR) wavelengths; and chemical reactions, which, when forming the maser molecule, leave it in the upper state of a maser transition.

Maser sources are almost invariably small: not in an absolute sense, as many are solar-system sized, some even light years across, but they are very compact relative to the environment in which they are found. For example, in regions where stars much more massive than the Sun are forming, maser spots are smaller than the region

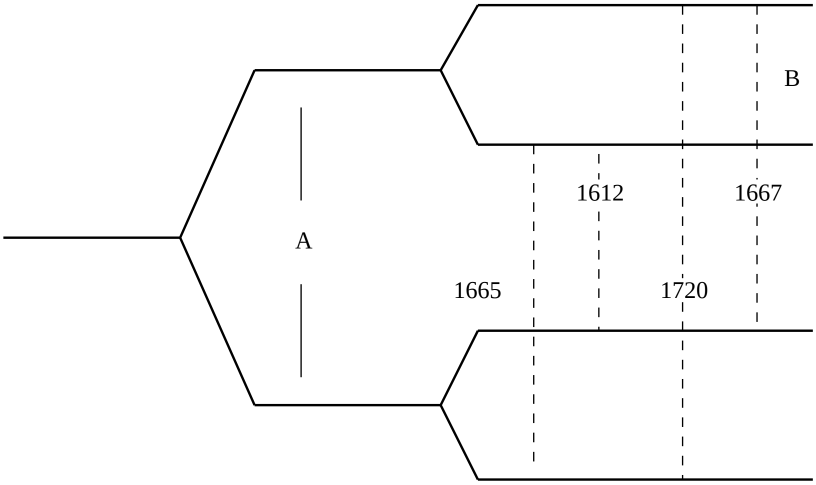

Figure 1. A schematic diagram of the lowest rotational state of the OH molecule. Transitions observed as masers have their frequencies marked in MHz. Energy splittings are due to (A) an interaction between the rotation of the molecule and electronic angular momentum (Lambda doubling); and (B) an interaction between the electronic spin angular momentum and the spin angular momentum of the hydrogen nucleus (hyperfine splitting). The splittings are not shown to scale. The next two higher rotational states are similar, giving rise to groups of potential maser transitions near 6000 and 4600 MHz, respectively.

by a factor of about 1000. The small relative size of the maser sources makes them extremely useful: they can give us diagnostics of their environments with unrivalled spatial precision.

3. Galactic masers in star-forming regions

Stars that are much more massive than the Sun also pour much more energy into their environment during their lifetimes, including their formation. As these stars form, some of their energy often goes to pump maser emission, which is observed to come from many transitions in at least six different molecular species, though not all from the same source. Masers from different species and different lines appear to inhabit rather different regions within a given source, and this reflects the different pumping requirements of the various transitions and molecules. Of course, as the young stellar object (YSO) at the heart of a source ages, conditions in its surroundings may evolve to favour a different set of masers.

As a massive YSO evolves, it becomes hot and begins to emit copious quantities of ultraviolet (UV) radiation, which ionizes the hydrogen in the surrounding gas, vaporizes the icy mantles of dust grains, and introduces a general outflow to the motion of the circumstellar material. When the region of ionized hydrogen (HII region) is very young and small, it is referred to as an ultra-compact HII region (UCHII) and OH masers form close to the boundary between the UCHII and the surrounding molecular gas. The OH masers appear in several lines (see figure 1) but the 1665 MHz transition is the brightest and most common (Caswell & Haynes 1987). The sites of the OH masers may be either in the disc of accreting matter around the star, when the magnetic field is quite ordered, for example in W75N

(Hutawarakorn & Cohen 1997), or in a more disturbed region (like W3(OH)). This siting probably depends on the evolutionary state of the young stellar object, which destroys the disc as its HII region grows (Cohen 1989). Perhaps the most remarkable feature of OH masers in star-forming regions is that many of them are 100% circularly polarized, though some elliptically and linearly polarized masers are also observed (Garcia-Barreto *et al.* 1988). Polarization and the Zeeman splitting of their spectral lines allows us to learn a great deal about the magnetic fields local to the masers. In particular, amplification along the magnetic field lines is the probable means of developing very high degrees of circular polarization (Gray & Field 1994). Sources that are probably disc like can be analysed using the polarization properties of maser spots. The apparently disordered field of the W75N source can be understood on the basis that we see masers from both the topside and underside of a circumstellar disc (figure 2).

Methanol masers in star-forming regions can be divided into two distinct types, classes I and II, depending the set of transitions present (Batrla *et al.* 1987). The type II sources, like OH masers, appear to be associated with UCHII regions. In some cases, OH and methanol regions appear to be close together and may even overlap. Groupings of class II masers are linear, with a velocity gradient consistent with rotation, and these objects are probably associated with accretion discs around massive YSOs, like the younger OH sources (Norris *et al.* 1998). Variability is on similar time-scales to that of OH, with changes typically over years (Moscadelli & Catarzi 1996). Class I sources by contrast appear spectrally and spatially consistent with turbulent motions and may mark an even earlier stage in the evolution of the YSO, prior to the formation of the UCHII (Sobolev *et al.* 1998).

Some of the energy injected into the interstellar medium (ISM) by YSOs is in the form of sound waves, which break and form shock waves in the lower density surroundings of the star. If these shock waves are not severe enough to dissociate water, they generate conditions in the gas behind the shock wave that are ideal for forming water masers via a predominantly collisional pumping scheme (Elitzur *et al.* 1992). Water masers are, invariably, associated with shocks in star-forming regions. Like OH and methanol, water can mase in many transitions, ranging in frequency from 22 GHz up to at least 658 GHz (Menten & Young 1995). There are also two subtly different types of water molecule with different sets of transitions. The shock waves that form the water masers can be consistent with generation by supersonic turbulence in some sources, but in others they appear closely linked with the positions where bipolar outflows from the poles of the YSO interact with the background medium (Reid *et al.* 1995). Water masers in star-forming regions have the highest brightness temperatures of all types, and the luminosities can exceed the entire output of the Sun. They are also highly variable on time-scales of weeks to months. Sometimes a burst occurs, in which a maser feature can become brighter by a factor of ten or more (Boboltz *et al.* 1998).

Other masers worthy of note from star-forming regions are ammonia, which Kraemer & Jackson (1995) place at the ends of high-velocity bipolar outflows from YSOs, but which are not associated with any other type of maser. Formaldehyde and SiO masers are interesting because of their rarity. Formaldehyde masers at 6 cm wavelength are known from only three Galactic star-formation regions; a survey by Mehringer *et al.* (1995) of 22 similar regions found no additional masers. The SiO masers, found frequently in circumstellar envelopes (see below) were originally

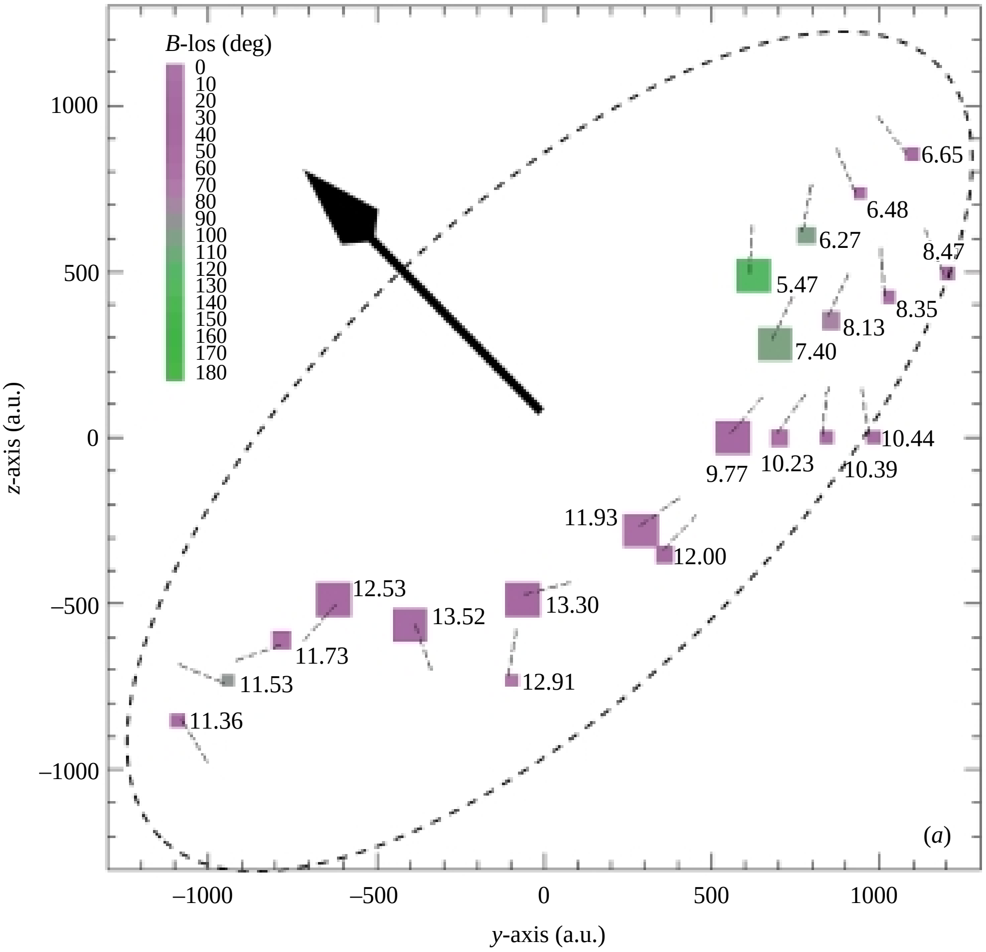

Figure 2. The results of a computer simulation of the polarized masers in the W75N star-forming region. In (*a*), the masers begin amplifying at the disc plane, those in (*b*) begin 25 AU below the plane. The model disc is tilted at 45° to the left and 45° towards the observer. Magnetic-field lines, represented by the dashed lines in the diagram, can be seen to have rotated on passing through the disc plane, and a combination of maser sites from figure parts (*a*) and (*b*) can explain the mixture of polarization planes observed from this source.

detected towards a star-forming region, but since then, only two more have been discovered.

4. Galactic masers in circumstellar envelopes

When stars reach an advanced stage of evolution, they become cooler and swell to form red-giant or red-supergiant objects, depending on their mass. These stars eventually reach a stage where they become variable and, at least for the lower-mass stars, the variability is pulsational. The pulsations drive shock waves into the stellar atmospheres, which become dense and undergo rapid mass loss, which can

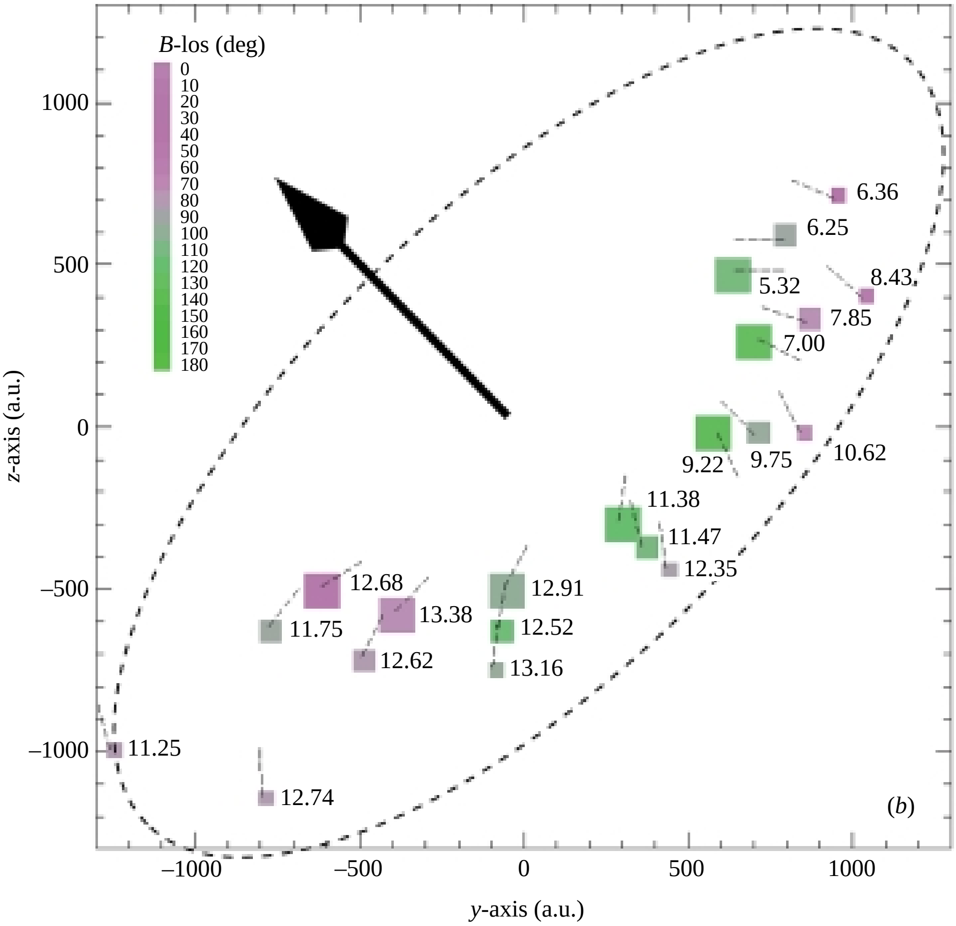

Figure 2. (*Cont.*)

exceed one Earth mass per year. These dense distended atmospheres, or circumstellar envelopes (CSE), are the sites of a rich assortment of circumstellar masers. As the stars evolve further, the envelope structure tends to become more opaque and changes in composition. One class of star, the OH/IR stars, are identified through their maser and infrared emission and their envelopes are completely opaque to visible radiation.

The maser species present in a CSE depend strongly on its composition, which is a function of the evolutionary state of the star. Initially, envelopes have an excess of oxygen over carbon (M-type or oxygen rich): chemical reaction networks dictate that all the carbon atoms in the CSE are bound as CO and that the masers observed are based on the oxygen-based species SiO, H_2O and OH. As the star evolves, internal convection raises recently nucleosynthesized carbon to the surface and, after passing through an intermediate (S-type) phase in which the carbon and oxygen abundances are similar, the CSE becomes carbon rich (C-type). C-type CSEs have hydrogen cyanide (HCN) and, very rarely, CO masers. Throughout this sequence, the stellar evolution proceeds ever more rapidly, and, consequently, we see far fewer envelopes of C-type than of M-type.

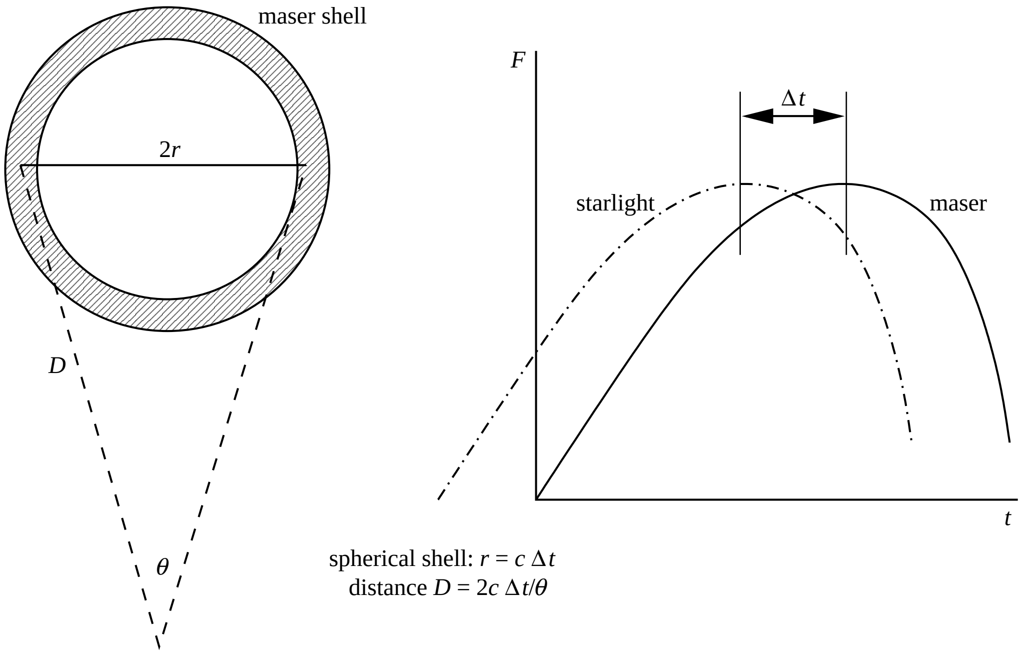

Figure 3. A method of measuring stellar distance using 1612 MHz maser shells. An interferometer, such as MERLIN, measured the angular diameter, θ, related to the true diameter $2r$ and the distance D. The radius, r is calculated based on the time lag between changes in the starlight and the maser, based on the light travel time from star to shell.

(*a*) *Oxygen-rich envelopes*

Stars with M-type envelopes have up to three concentric zones of maser emission. Images taken with the VLBA and VLBI interferometer networks (Diamond *et al.* 1994; Greenhill *et al.* 1995) have shown that the SiO masers lie closest to the stellar surface, sampling the densest, hottest and most energetic region of the envelope within about three stellar radii of the surface. Further out, at roughly ten stellar radii from the surface, are water masers, detected at several frequencies by Yates *et al.* (1995) and closely associated main line (1665 and 1667 MHz) OH masers. Finally, at 50 or more stellar radii lies the outermost shell, composed of 1612 MHz OH masers. The development of the three shells is probably also evolutionary according to Lewis (1996), developing from inside to outside, and certainly many stars have only one or two of the shells.

Interferometer measurements of these masers with instruments like MERLIN show that the structure is that of a thin spherical shell, dominated by radial amplification: the caps of the shell in front of, and usually behind, the star appear much brighter than the limbs. The double-peaked spectral structure of these masers indicates that they are situated in the outer, smoothly outflowing region of the CSE. A useful method of estimating the distances to these stars, based on the phase lag between variations of the starlight and maser, has been developed (figure 3, see also Cohen (1989)).

These masers are important because of proper motions and are found in an intermediate zone where outflow has been established in the CSE, but where it is still subject to shocks and probably to turbulent motions. There are many water frequencies emitted, some of which are probably very closely associated spatially (Yates *et al*. 1995), and others are not. Interferometer observations show the masers grouped in a rather indistinct ring structure, indicating a combination of radial and tangential amplification (see, for example, Richards *et al*. 1996). The OH mainline masers probably form from the dissociation of water molecules by ultraviolet starlight at the outer edge of the zone. Proper motions of these masers, combined with a suitable model of the geometry, can yield distances via the method of moving-cluster parallax.

The structure of the energy levels of SiO, with masing transitions marked, is shown and explained in figure 4. Masers have been detected from vibrational states $v = 0$ to $v = 4$, but those in $v = 1$ and $v = 2$ are the strongest. An example of a 300 GHz $J = 7$–6 maser is shown in figure 5. Interferometer images show that, at least at 43 GHz ($J = 1$–0), the masers form a ring structure around the star that varies with time (Diamond *et al*. 1994), with spots directly in front of the star being rare and weak. This suggests that amplification is predominantly tangential. In the SiO maser zone, the outflow and mass-loss processes are only just being established: the dominant motion of the envelope is pulsational, and both expansion and contraction of 43 GHz maser rings have been detected (Boboltz *et al*. 1997). The whole structure of the SiO zone appears to be intimately tied to the periodicity of the star. Hydrodynamic models of the envelope, supported by observations (Humphreys *et al*. 1996) suggest that shock waves sweep outward through the envelope, so that a clump of gas supporting an SiO maser should experience a sequence of violent outward accelerations by the shock waves followed by slow deceleration under gravity. Chemical considerations indicate that the SiO maser zone is inside the likely radius for the formation of silicate dust, which would deplete most of the SiO from the gas phase to form grains. A computer simulation of this shell has also been produced with the ultimate aim of calculating mass-loss rates as a function of radius and time and some frames from this film are shown in figure 6*a*–*d*.

Polarization is frequently observed in SiO masers and is usually linear. A very interesting experiment would be to follow the planes of polarization through a stellar cycle, since a rapid change of the polarization plane would probably fix the position of the shock wave at any phase of the stellar cycle. Tracing the shock wave position is vital for fixing the phase relationship, presently poorly known, between the optical light curve (phase zero at maximum light) and theoretical models (phase zero at maximum outward velocity of the sub-photospheric layers driving the pulsation). One possible method is to use high-frequency SiO masers, for example $v = 1$, $J = 7$–6 at 300 GHz (figure 5), which require very high temperatures, only found just behind the shock wave, to trace its position. However, at present no telescope exists that is capable of producing high-resolution interferometer images at such a high frequency; astronomers await the ALMA array due in service in 2007.

(*b*) *Carbon-rich envelopes: why are* CO *masers so rare?*

(i) HCN *masers*

Hydrogen cyanide is the only strong maser found in C-type CSEs. There appear to be several frequencies, but the original detection, in a vibrationally excited form

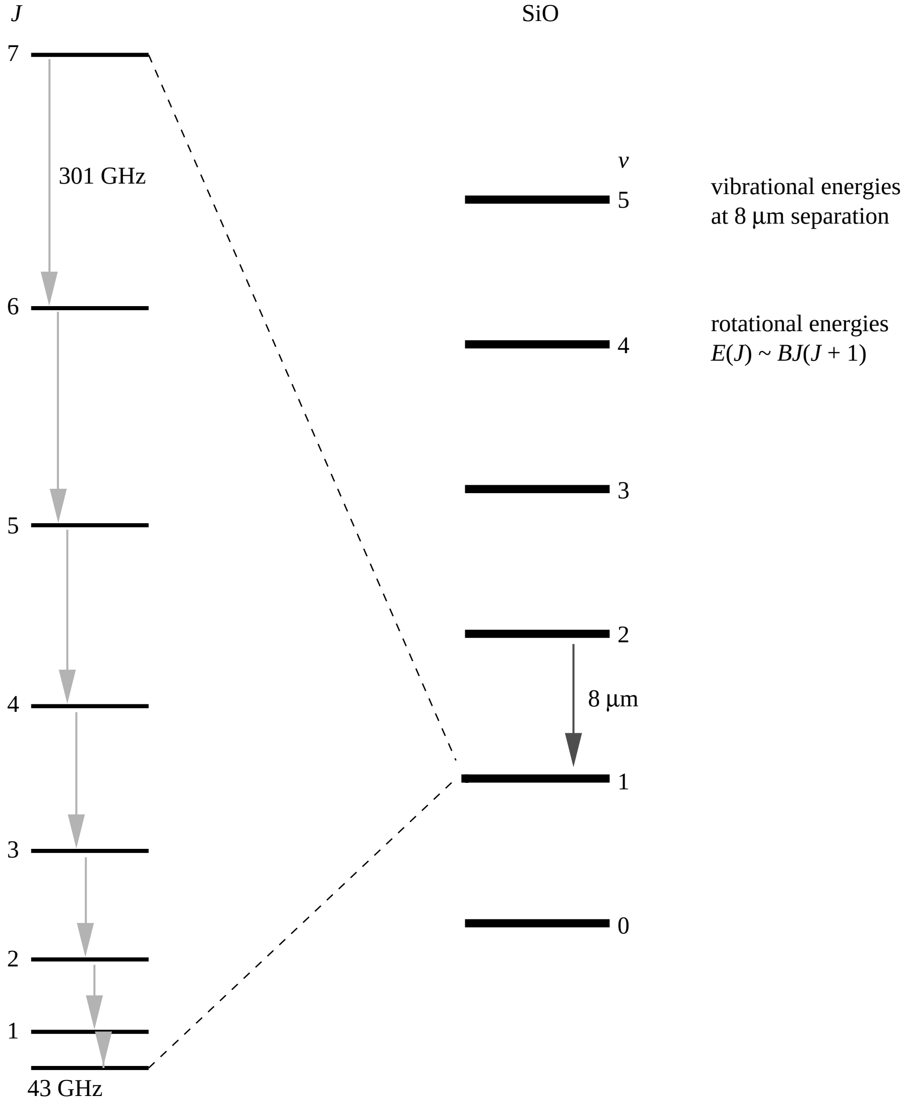

Figure 4. A schematic diagram of the energy levels of the SiO molecule. Roughly equally spaced vibrational states are linked by radiation of wavelengths near 8 µm. Within each vibrational state is a stack of rotational states with increasing quantum number J. B is the rotational constant of the molecule. Masers have been observed from the vibrational states 0–4 and those transitions observed as masers in the $v = 1$ state are marked. Frequencies range from 43 GHz for $J = 1$–0 to 301 GHz for $J = 7$–6.

of the molecule, at 89 GHz by Guilloteau *et al.* (1987) appears to be present in envelopes with moderate mass-loss rates. Detection rates in a survey were about 20% (Lucas *et al.* 1988).

Another maser in the vibrational ground state has also been detected by Izumiura *et al.* (1995) towards C-type stars, which are optical stars; they have quite thin envelopes with very low mass-loss rates. There is, therefore, a problem in observing

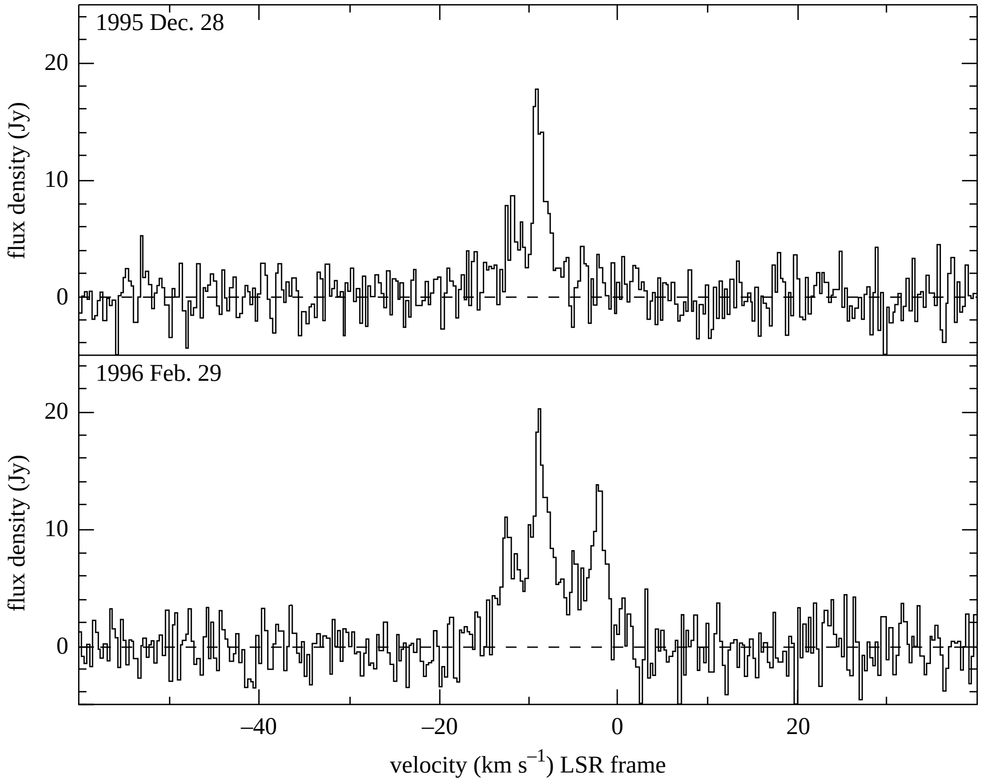

Figure 5. An example of the spectrum of a $v = 1$, $J = 7$–6 SiO maser from the Mira variable star R Hydrae, observed with the James Clerk Maxwell Telescope, Mauna Kea, Hawaii. Note the change in the spectrum over the period of two months, with new narrow features appearing to both the blueshifted and redshifted sides of the central core.

the heavily obscured carbon stars, which, at present, have no maser tracer. The frequencies of the HCN masers are unfortunately just a little too high to be traced with present VLBI networks in the same manner as SiO, so the full diagnostic power of these objects must also wait for an improvement in interferometer technology.

Although CO is a very abundant molecule in CSEs, as well as the rest of the ISM, there is, to date, just the unique maser source in the envelope of V Hydrae (Zuckerman & Dyck 1986). The pumping mechanism has been analysed by Piehler *et al.* (1991) and there appear to be two important factors. Firstly, CO is just too abundant: the opacity in two vital FIR pumping lines is sufficient to destroy the pumping mechanism by weighting the decay of a high-lying energy level away from the upper level of a potential maser. Secondly, there is much CO in the stellar photosphere, where it causes broad absorption features that reduce the intensities of FIR radiation, and so further reduce the efficiency of the pump.

5. Megamasers

Masers of some of the types mentioned above have also been detected in nearby galaxies. Megamasers, however, are a completely different source type, which is far more energetic than the Galactic masers discussed so far. The host galaxies of mega-

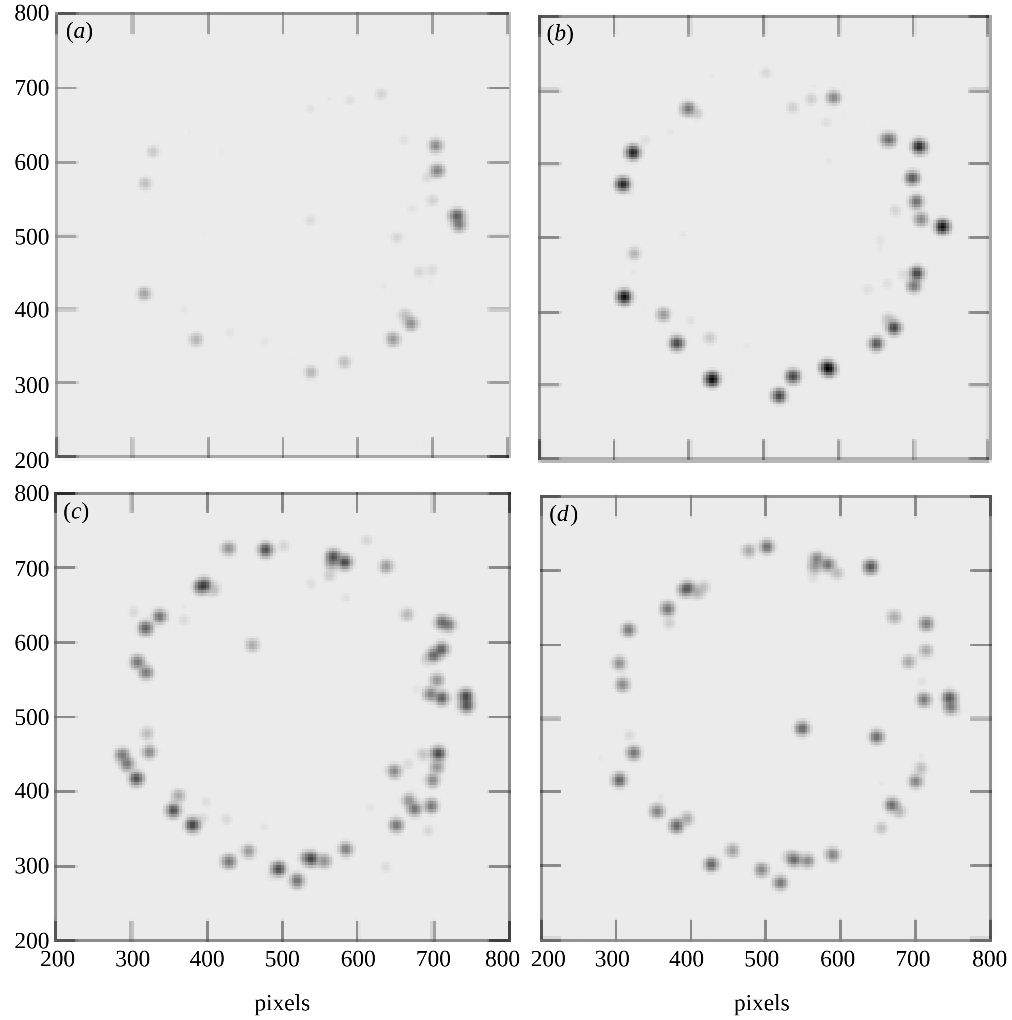

Figure 6. A sequence of computer simulated images of SiO masers at 43 GHz ($v = 1$, $J = 1$–0) in the pulsating atmosphere of a Mira variable. Each pixel is about 1/200 of an AU. The period of pulsation of the modelled star is 1 year and the sequence of images cover 1/3 of the period, at intervals of approximately 30 days. (*a*) is at a phase of 0.58; (*b*) at 0.67; (*c*) at 0.75; and (*d*) at a phase of 0.83. The phases are given as fractions of the period. Note that the modelled masers both move and change in brightness over the timespan of the model.

masers all appear to be peculiar or disturbed in some way. They may be tidally perturbed, undergoing an intense burst of star formation or a merger event, or have a non-thermal active galactic nucleus (AGN). Galaxies with an AGN are believed to be powered by a supermassive black hole in the core. The common factor between all these apparently disparate host galaxy types is that they are all ultraluminous in the infrared, which allows for efficient searches (Unger *et al*. 1986). This emission is almost certainly from dust that absorbs ultraviolet radiation from the active region and re-radiates it in the IR. Associated with the dust, and protected from the UV by it, are molecules, and the OH and water molecules form the megamasers.

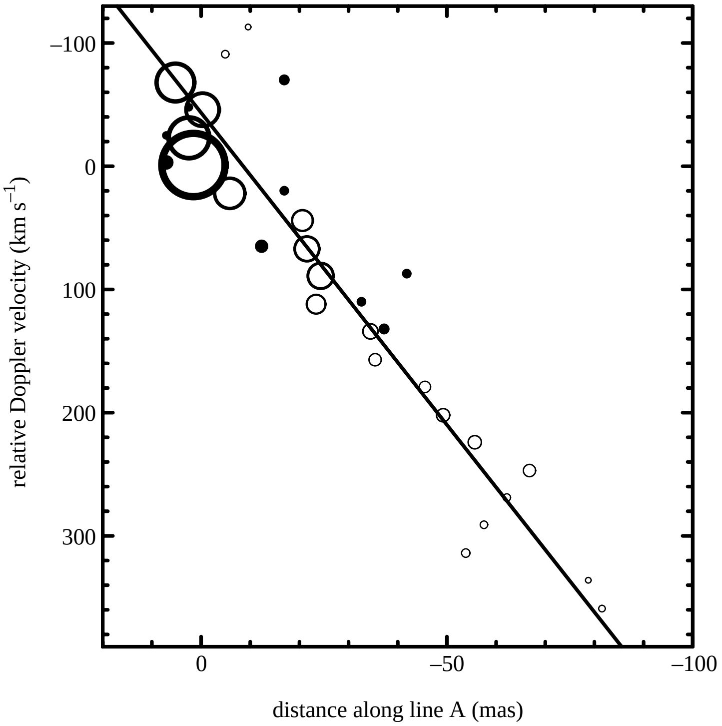

Figure 7. A plot of the OH maser motions in the core of the megamaser galaxy MKN273. Radii of spots or circles are proportional to the brightness of the features. Note that measured velocities of maser clumps follow a close line, indicating mainly ordered motion. The velocities are also proportional to distance in milliarc seconds along a line, A, estimated to be parallel to an edge-on disc. The motions with velocity directly proportional to distance are consistent with a solid-body type of rotation, expected for the mass distribution in a galactic nucleus. This plot can be used to estimate the nuclear density and binding mass.

Apart from the obvious difference in overall luminosity, OH megamasers differ in several important respects from Galactic masers. The spectra are very broad, typically several hundred km s^{-1} wide. Sometimes there are additional wings, blue- and redshifted from the central emission core, separated from it by several hundreds more km s^{-1} (Staveley-Smith *et al*. 1987), so that the width of the entire spectrum can exceed 1000 km s^{-1}. The dominant OH line in megamasers is the 1667 MHz line, rather than the 1665 MHz line in Galactic masers. The OH megamasers are less polarized and no Zeeman splittings have been measured.

Interferometer measurements show that the clouds that contribute to the megamaser spectra are only a few light years across, and, in some objects, can be seen to have well-ordered motion. In the case of water megamasers, the motion traced can often be understood in terms of rotation as part of a disc around the central black hole (Moran 1998). Binding masses can be determined from the rotational speeds, distances from proper motions and magnetic fields appear to be weak. In the spectacular case of NGC4258, the binding mass for the central object was 3.5×10^7 solar masses. In the case of NGC3079, the motion is much less ordered and has been modelled as rotation plus strong turbulence by Trotter *et al*. (1998).

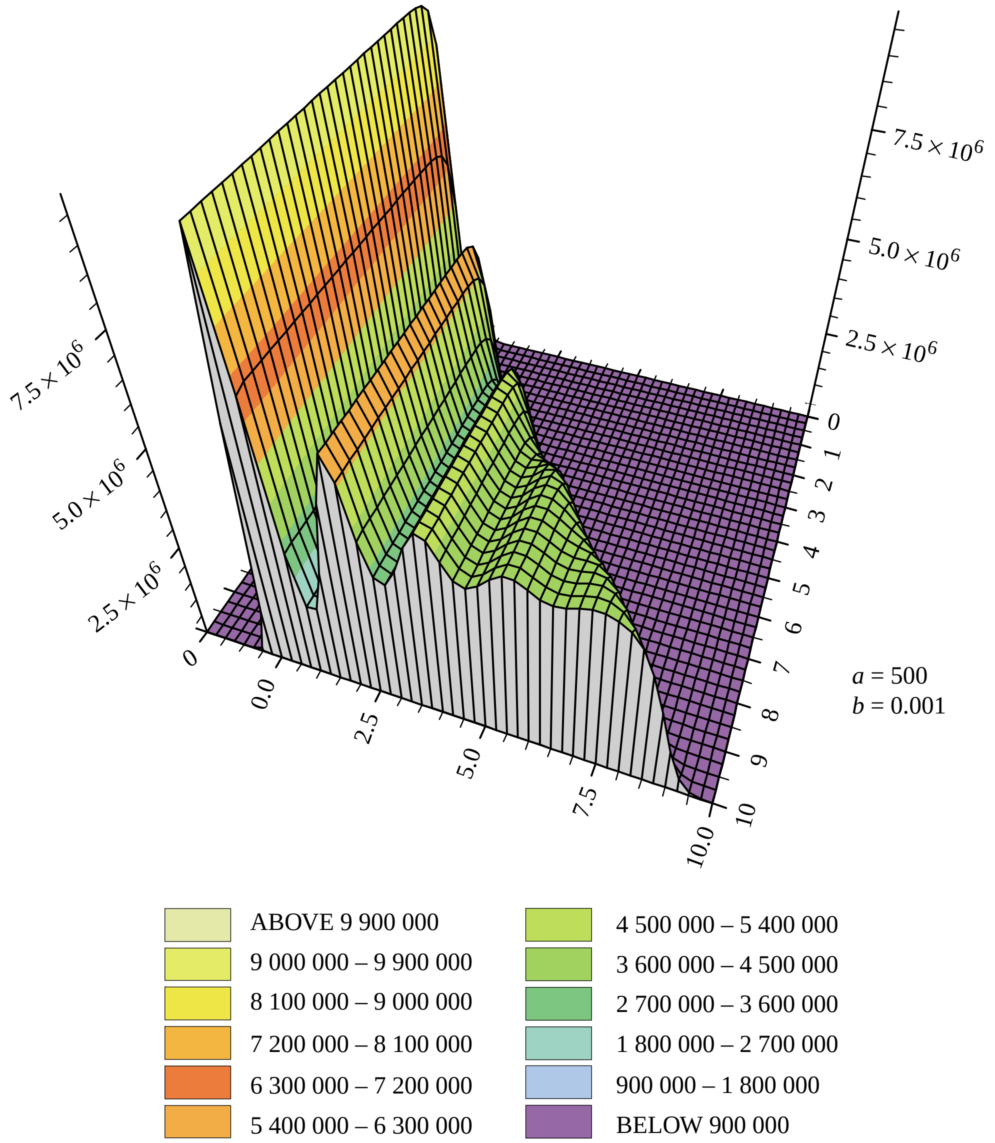

Figure 8. A computer model of a maser propagated through a constant velocity gradient. Velocity increases to the right in units of Doppler widths. Initially, the maser grows from the back of the figure to the front on the left-hand side and saturates to a flat peak. As the molecular response moves to the right, the saturation is removed catastrophically and a new peak begins to appear close to the new molecular line centre. The grey shaded region on the front of the diagram corresponds to the spectrum that would be seen by an observer.

OH megamasers also sometimes appear to be formed from elements of a rotating molecular torus. Recent observations of MKN273 with the MERLIN interferometer allowed the calculation of a central density for the nucleus of some 10 000 times greater than in the solar neighbourhood on the basis of a rotation curve (see figure 7).

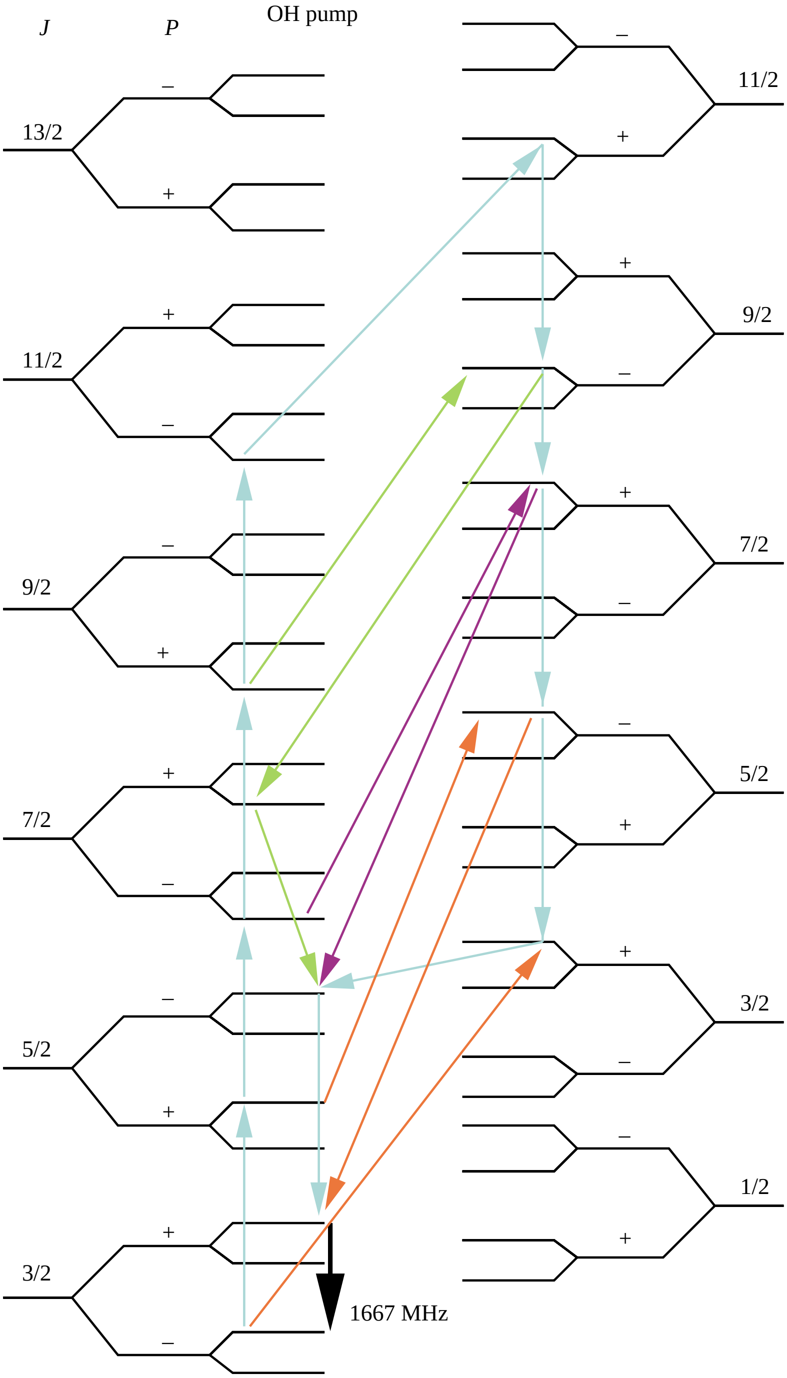

Figure 9. A possible pumping scheme for the OH 1667 MHz transition, dominated by radiative pumping routes. The most popular route is marked in pale blue, followed by the green, purple and red routes in order of decreasing importance. All transitions marked are in the FIR with wavelengths in the approximate range of 30–150 µm.

6. Supernova remnants

A relatively new source type is the interaction region between supernova remnants (SNR) and dense molecular gas. In a recent survey, no fewer than 33 detections of 1720 MHz OH masers were made from a sample of 75 SNRs (Green *et al*. 1997). When correlated with observations of CO-rich gas near the maser sites by Frail & Mitchell (1998), the masers appear to be associated with thin molecular filaments that correlate in position with synchrotron continuum emission, generated by relativistic electrons gyrating in a magnetic field. Models have shown that the masers have a mixture of chemical and collisional pumping. The idea is that magnetically modified weak shock waves (C-type) form water behind them, which is then photodissociated by soft X-rays from the SNR to yield the necessary OH (Wardle *et al*. 1998). The mechanism does not work for stronger J-type shock waves. The SNR masers had many spots at the resolution of the very large array (VLA) when observed by Claussen *et al*. (1997). The VLA observations had full polarization information and revealed quite a weak magnetic field of 20 μT. The velocity spread of the spots was a few km s^{-1} and there is a suggestion that the maximum amplification occurs when the acceleration due to the SNR shockwave is perpendicular to the propagation direction of the maser.

7. Other sources

The supergiant star MWC349 has an envelope that supports hydrogen-atom-recombination line masers. These involve electronic transitions, involving changes in the principal quantum number, n, like the well-known Lyman and Balmer lines in the ultraviolet and visible regions, but they appear at microwave frequencies because they occur between high-lying states with small energy differences. The range of values of n that can support inversions is limited to the approximate range 10–40 (Strelnitski *et al*. 1996). The pump involves ultraviolet radiation and electron collisions.

If the sources discussed so far all seem very remote, there are astrophysical masers much closer to home, within our own Solar System. The recent impressive show provided by the comet Hale–Bopp in 1997 had its radio counterpart in OH maser emission at 1667 MHz, observed by Galt (1998) between late February and the beginning of June. Interestingly, after the main cometary emission had died away, a new spike appeared, where the cometary coma had amplified a background source (see § 9).

The final type of astrophysical maser needs no molecules, and, hence, no inversion in the usual sense of the word. These are free-electron masers, and most are based on the cyclotron mechanism. An electron moving perpendicular to a magnetic field gyrates around the field lines with a characteristic frequency, the gyrofrequency, which is proportional to the magnetic-field strength. An electromagnetic field that has a frequency resonant with the gyrofrequency can amplify at the expense of the energy of the electrons; cyclotron masers, therefore, appear at integer multiples of the gyrofrequency but amplify best for small multiples. Since no molecules are involved, free-electron masers can appear from very-hot source regions, for example, solar flares and, more generally, from the magnetospheres of stars and planets. Using the highly useful ability of maser amplification to make very small objects look very bright, a search has been made for extra-Solar System planets on the basis of their cyclotron maser emission, and several large-planet or brown-dwarf star candidates were detected by Dulk *et al*. (1997).

8. The theory of astrophysical masers

The gases in which astrophysical masers form are non-equilibrium systems, which means we cannot use the Boltzmann formula to calculate the fraction of the total population of the molecule of interest that will be in each of the energy levels of the molecule; if we could, there would be no inversions, and no masers! With the easy option removed, the level populations must be calculated using master equations. These basically keep account of all processes that transfer population between any one level and all the others. If the overall inward and outward rates are equal, we have a steady-state problem, if they are not, we have a time-dependent problem. The processes that move populations are a combination of collisions, non-maser radiation processes and the effects of maser lines themselves (saturation). Obviously, the more levels we wish to include in the model, the more complex the problem; analytic solutions are rarely possible for anything other than an idealized two-level system in a simple imposed geometry.

For the usual assumptions made up to about 1990, I shall again refer the reader to Cohen (1989), and Elitzur (1992). Models worthy of note should go beyond these assumptions. Efforts to include the magnetic-field dependence and polarization in OH, so obviously necessary from observations, have been fairly successful (Gray & Field 1995). It is also desirable to have models in which the radiation transfer is solved exactly, rather than making the usual local approximation. Such models have been applied to OH (Collison & Nedoluha 1995) and to H_2O (Yates *et al*. 1997). Real maser sites are almost invariably dynamic environments, so velocity fields are another important ingredient. Figure 8 demonstrates a peculiar oscillatory effect that can occur when a maser is propagated down a velocity gradient (Field *et al*. 1994).

Of course, a solution for our chosen set of energy-level populations is only as good as the molecular data that go into the model. Obtaining these data requires interdisciplinary collaboration between astronomers and theoretical chemists. Collision cross-sections for the maser molecules with H and H_2 are hard to come by and are difficult to calculate. I should mention a set calculated for OH on H_2 by Offer *et al*. (1994) and a new set being developed for SiO on both H and H_2. In spite of all the uncertainties, modellers have been remarkably successful in deriving pumping schemes for most of the maser species. It is possible to trace the pumping scheme via recording the most significant computational operations made during the final iteration of the solution, and some preliminary results for the 1665 MHz maser are shown in figure 9.

9. The future of theory and observations

In terms of theory, advances should, and probably will, come in the direction of making models more realistic: old approximate methods will increasingly become replaced by models that are fully self-consistent, include chemical networks to produce the maser molecules, are time dependent, and have much less restriction to well-defined geometries such as spheres and cylinders. For some special problems, maser initiation for example, fully quantum-mechanical treatments, where both the radiation and molecular ensemble are quantized, are desirable.

Increasing computer power will enable models to become ever more sophisticated. Indeed, without this numerical improvement, much of the progress discussed in the first paragraph would not be possible. However, the computer models should also become cleverer, for example by automatic tracking of important elements in the pumping scheme, so that a summary of why the solution looks the way it does is readily available to the investigator.

One area of theory in which I am extremely interested is that of generating a theory of broad-band maser radiation that is sufficiently accurate to address the problem of a proper coherence function for astrophysical masers. Such a theory would be complementary to a difficult but feasible experiment that could actually prove that astrophysical masers arise via stimulated emission. What is required is a resolution that picks out the response of individual velocity subgroups of molecules; this is about 0.01 Hz for 1665 MHz OH masers. Observing over such a tiny bandwidth should show whether or not the radiation has the properties of chaotic or coherent light. In fact, the coherence should be partial, and predictable by the accurate theory. Any result that fitted the partly coherent, rather than the chaotic, form would prove that maser sources truly are masers.

The first observational development that will revolutionize maser astrophysics is a steady improvement in interferometer technology. Already, networks like the American VLBA and European EVN systems are capable of semi-automatic operation, allowing time-series observations of objects like the SiO masers in CSEs. Again, computing power is vital: quantities of data are now being routinely processed that would have been unthinkable just a decade ago. Observations are now also routinely phase referenced (a nearby continuum source is used to calibrate the phase of the masers), which allows very-high absolute position accuracy. This is extremely important in that for the first time it allows us to realistically ask the question of whether two masers at different frequencies really amplify through the same column of gas and can therefore be used to test theories of competitive gain. Resolution is also likely to improve as antennas are based in orbit.

Interferometry will make another huge advance with the advent of the Atacama large millimetre wave array (ALMA); a huge international instrument with baselines up to 10 km, which will be able to operate at up to the highest submillimetre frequencies available to ground-based observers. This object will vastly improve the positional information for all astrophysical masers above *ca.* 80 GHz.

The recent flight of the ISO satellite allowed observers to look not at the maser lines of OH, but at the FIR lines that pump them. Where results have been compared with the predictions based on pumping schemes required to sustain masers, agreement has been encouragingly good (see, for example, Thai-Q-Tung *et al.* 1998). There is also a possibility that FIRASERs, or far-infrared lasers, may exist well beyond the highest frequencies observed from the ground. Current observations have been inconclusive, but a successor to ISO is planned!

Megamasers are extremely bright and can, therefore, be seen at great distances, or, equivalently, at high redshifts, so they are important cosmologically. There are two important tests on the evolution of the Universe that can be applied using megamasers. The first is to study the rate of merging events in young galaxies (Briggs 1998). Remember that mergers are an important subclass of megamasers, so the number of detected mergers from megamaser observations can be checked against the predictions of cosmological theories. The second test is to use megamasers to study molecular abundance in the early Universe. The oxygen in OH and water must come from nuclear processing inside stars, so it would be expected to be rarer in young galaxies, so affecting the abundance and/or intensities of megamasers at high redshift. The problem with such observations is that the redshift moves the target frequency range down to the 200–1000 MHz range, where pollution from commercial communications equipment is already making ground-based radio astronomy very difficult. What is required is a fully space-based radio observatory.

A space-based system is definitely required to observe in the last great unexplored observing band. The ionosphere, which allows us to bounce short-wave radio signals around the world, also bounces back radiation at similar frequencies from space, so we can see nothing at frequencies below about 10 MHz. We do not expect to see molecular emission at these very low frequencies (VLF), but cyclotron and other free-electron masers could be very bright. Recall that we expect masers at multiples of the gyrofrequency, which is proportional to magnetic-field strength. Earth-like planets have fields that might produce cyclotron masers in the VLF range, so the VLF observatory would be an important step in the search for extraterrestrial life. An instrument to be based on the far side of the Moon has been mooted by the European Space Agency (ESA).

Astrophysical masers are natural amplifiers. Would we be the first civilization to think of using them to broadcast our presence to others? With only limited power available, an effective way of boosting one's signal to the rest of the Galaxy would be to amplify it through a natural maser region (R. J. Cohen 1998, personal communication). It could be, for example, a known water maser. The much geometrically diluted signal would then get a free amplification by a factor of up to 10^{12} times before going on its way. Remember that a natural background signal was detected after being amplified through the coma of comet Hale–Bopp. Perhaps some future element of the SETI programme should look at star-forming regions, not because of what is in them, but because of what might be behind them.

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