Astrophysical masers

by Pawel Lachowicz

What is maser and maser emission?

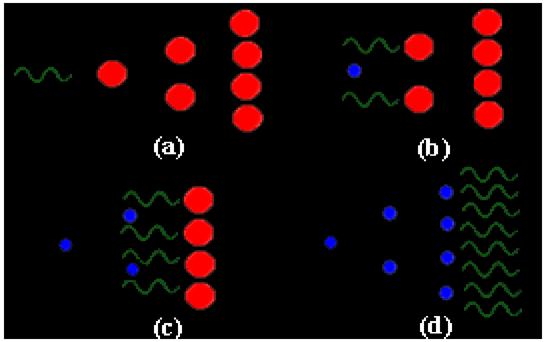
MASER stands for Microwave Amplification by Stimulation Emission of Radiation

The fundamental physical principle motivating the MASER is the concept of stimulated emission, first introduced by Einstein in 1917.

Absorption - if an atom absorbs a photon it goes to a higher energy state.

Spontaneous Emission - atoms don't like to stay in high energy states so after absorbing a photon and going to a higher energy state, they will move to a lower energy state, emitting a photon. This is called "spontaneous emission" because no outside influence triggers the emission. Normally the average lifetime for spontaneous emissions by excited atoms is around 10e-8 seconds (that is, the atom or molecule will usually take around 10-8 seconds before emitting the photon). Occasionally, however, there are states for which the lifetime is much longer, perhaps around 10e-3 seconds. These states are called *metastable*. *Metastable* emission levels are essential for a working MASER.

Stimulated Emission - with stimulated emission, a photon of the absorption wavelength, *k* , is fired at an atom already in its high energy state. The atom absorbs this photon, and then quickly emits two photons to get back to its lower energy state. Thanks to quantum mechanics, both of these newly emitted photons are of wavelength *k*



The emission from an astrophysical maser is due to a single pass through the gain medium.

Astrophysical requirements

* there must be *velocity coherence* along the line of sight so that Doppler shifting does not prevent inverted states in different parts of the gain medium from radiatively coupling

* *polarisation* in astrophyscial masers will only arise in the presence of a polarisation-state dependent pump *or* of a magnetic field in the gain medium

* the radiation from astrophysical masers can be quite weak and may escape detection due to the limited sensitivity of astronomical observatories *or* due to the overwhelming spectral absorption from unpumped molecules of the maser species in the surrounding space (the latter can be fixed with the present ways of improvement interferometric techniques (e.g. for the VLBI observations)

What for?

The major use of maser study is that they give valuable information on:

* the conditions in space (temperature, number density, magnetic field and velocity) in the most interesting of environments:
    * stellar birth and death
    * the centre of galaxies containing black-holes

The conditions involved in these events still need more accurate measuring so that *theoretical models can be refined or revised*.

Prior to discovery of maser emission

* before 1965 many people thought that molecules could not exist in space, so the emission was at first linked to an interstellar species named *Mysterium*

* the emission was soon identified as line emission from OH molecules in compact sources within molecular clouds

The discovery of maser emission (1)

In 1965 an unexpected discovery was made by Weaver *et alii* who detected emission lines in space of unknown origin at a frequency of 1665 Mhz.

Followed soon after by detection of:

* H_2O emission in 1969
* CH_3OH emission in 1970
* SiO emission in 1974

all coming from within molecular clouds.

Termed as masers as from their narrow line-widths and high effective temperatures it became clear that these sources were amplifying microwave radiation.

The discovery of maser emission (2)

discovered next:

* around highly evolved Late type stars
  - OH emission in 1968
  - H_2O emission in 1969
  - SiO emission in 1974
* in external galaxies in 1973
* in our Solar System
* in halos of comets

* in 1982 with the discovery of emission from an extra-galactic source (of L ~ 106x larger than any previous source). Termed as megamaser because of its great luminosity

Evidence for an *anti-pumped* (dasar) sub-thermal population in the 4830 MHz transition of formaldehyde (H_2CO) was observed by Palmer et al. (1969)

Detection: where or what and in what ?

band: FIR, optical, radio emission

target: molecular clouds, OH-IR stars, and FIR active galaxies

Maser emission: main players in the game

Species that have been observed in stimulated emission from astronomical environments

* OH
* CH
* H_2CO
* H_2O
* NH_3
* CH_3OH
* SiS
* HC_3N
* SiO, 29SiO, 30SiO
* HCN, $H_{13}CN$
* H

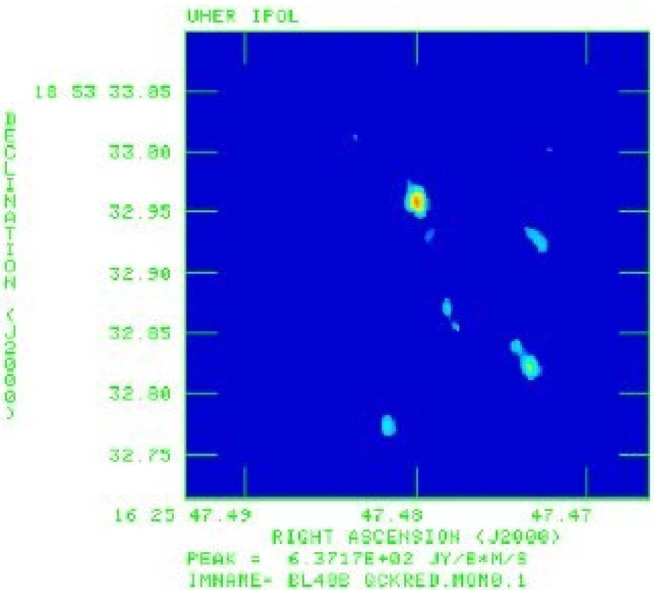
selected known astrophysical maser transitions (as for 2003, by Karl M. Menten)

Species	Transition	Frequency (MHz)	Source Type
OH $^2\Pi_{3/2}$	$J=\frac{3}{2}$, $F=1\rightarrow 2$	1612.2310(2)	SFR/O-CSE
	$F=1\rightarrow 1$	1665.4018(1)	SFR/O-CSE
	$F=2\rightarrow 2$	1667.3590(1)	SFR/O-CSE
	$F=2\rightarrow 1$	1720.5300(1)	SFR
	$J=\frac{5}{2}$, $F=2\rightarrow 2$	6030.747(5)	SFR
	$F=3\rightarrow 3$	6035.092(5)	SFR
	$J=\frac{7}{2}$, $F=4\rightarrow 4$	13441.4173(2)	SFR
OH $^2\Pi_{1/2}$	$J=\frac{1}{2}$, $F=0\rightarrow 1$	4660.242(3)	SFR
	$F=1\rightarrow 0$	4765.562(3)	SFR
H_2O	$J_{K_a,K_c}=\ 6_{16}\rightarrow 5_{23}$	22235.08	SFR/O-CSE
	$3_{13}\rightarrow 2_{20}$	183310.12	SFR/O-CSE
	$10_{29}\rightarrow 9_{36}$	321225.64	SFR/O-CSE
	$5_{15}\rightarrow 4_{22}$	325152.92	SFR/O-CSE
	$4_{14}\rightarrow 3_{21}$	380197.37	SFR
	$7_{53}\rightarrow 6_{60}$	437346.67	O-CSE
	$6_{43}\rightarrow 5_{50}$	439150.81	SFR/O-CSE
	$6_{42}\rightarrow 5_{51}$	470888.95	SFR/O-CSE
H_2O $\nu_2=1$	$J_{K_a,K_c}=\ 4_{40}\rightarrow 5_{33}$	96261.16	O-CSE
	$5_{50}\rightarrow 6_{43}$	232686.70	O-CSE
	$1_{10}\rightarrow 1_{01}$	658006.55	O-CSE
CH_3OH	$J_k=\ 5_1\rightarrow 6_0 A^+$	6668.5192(8)	SFR/Cl II
	$9_{-1}\rightarrow 8_{-2}E$	9936.202(4)	SFR/Cl I
	$2_0\rightarrow 3_{-1}E$	12178.597(4)	SFR/Cl II
	$2_1\rightarrow 3_0 E$	19967.416(33)	SFR/Cl II
	$9_2\rightarrow 10_1 A^+$	23121.024(1)	SFR/Cl II
	$3_2\rightarrow 3_1 E$	24928.70(10)	SFR/Cl I
	$4_2\rightarrow 4_1 E$	24933.468(2)	SFR/Cl I
	$5_2\rightarrow 5_1 E$	24959.080(2)	SFR/Cl I
	$6_2\rightarrow 6_1 E$	25018.123(2)	SFR/Cl I
	$7_2\rightarrow 7_1 E$	25124.873(2)	SFR/Cl I
	$8_2\rightarrow 8_1 E$	25294.411(3)	SFR/Cl I
	$9_2\rightarrow 9_1 E$	25541.43(10)	SFR/Cl I
	$10_2\rightarrow 10_1 E$	25878.18(10)	SFR/Cl I
	$12_2\rightarrow 12_1 E$	26847.27	SFR/Cl I
	$13_2\rightarrow 13_1 E$	27472.58	SFR/Cl I
	$14_2\rightarrow 14_1 E$	28169.52	SFR/Cl I
	$15_2\rightarrow 15_1 E$	28905.85	SFR/Cl I
	$8_2\rightarrow 9_1 A^-$	28969.90(10)	SFR/Cl I
	$16_2\rightarrow 16_1 E$	29637.11	SFR/Cl I
	$17_2\rightarrow 17_1 E$	30308.08	SFR/Cl I
	$4_{-1}\rightarrow 3_0 E$	36169.24(10)	SFR/Cl I
	$7_{-2}\rightarrow 8_{-1} E$	37703.72(10)	SFR/Cl II
	$6_2\rightarrow 5_3 A^+$	38293.50(10)	SFR/Cl II
	$6_2\rightarrow 5_3 A^-$	38452.60(10)	SFR/Cl II
	$7_0\rightarrow 6_1 A^+$	44069.49(10)	SFR/Cl I
	$5_{-1}\rightarrow 4_0 E$	84521.21(8)	SFR/Cl I
	$7_2\rightarrow 6_3 A^-$	86615.602(14)	SFR/Cl II
	$7_2\rightarrow 6_3 A^+$	86902.947914)	SFR/Cl II
	$8_0\rightarrow 7_1 A^+$	95169.44(10)	SFR/Cl I
	$3_1\rightarrow 4_0 A^+$	107013.85(10)	SFR/Cl II
	$9_0\rightarrow 8_1 A^+$	146618.82(10)	SFR/Cl I
	$8_0\rightarrow 8_{-1} E$	156488.95(10)	SFR/Cl II
	$2_1\rightarrow 3_0 A^+$	156602.42(10)	SFR/Cl II
	$7_0\rightarrow 7_{-1} E$	156828.52(10)	SFR/Cl II
	$6_0\rightarrow 6_{-1} E$	157048.62(10)	SFR/Cl II
	$5_0\rightarrow 5_{-1} E$	157178.97(10)	SFR/Cl II
	$4_0\rightarrow 4_{-1} E$	157246.10(10)	SFR/Cl II
	$1_0\rightarrow 1_{-1} E$	157270.70(10)	SFR/Cl II
	$3_0\rightarrow 3_{-1} E$	157272.47(10)	SFR/Cl II
	$2_0\rightarrow 2_{-1} E$	157276.04(10)	SFR/Cl II
NH_3	$(J,K)=\ (9,6)$	18499.390(5)	SFR
	(6,3)	19757.538(5)	SFR
	(7,5)	20804.830(5)	SFR
	(10,8)	20852.527(5)	SFR
	(11,9)	21070.739(5)	SFR
	(5,4)	22653.022(5)	SFR
	(6,5)	22732.429(5)	SFR
	(9,8)	23657.471(5)	SFR
	(3,3)	23870.129	SFR

The *amplification* or *gain* of radiation passing through a maser cloud is exponential. This has some consequences.

Consequences (1)

Beaming. Small path differences across the irregularly shaped maser cloud become greatly distorted by exponential gain. Part of the cloud that has a slightly longer path length than the rest will appear much brighter and so maser spots are typically much smaller than their parent clouds. The majority of the radiation will emerge along this line of greatest path length in a *beam*.



Rapid variability. As the gain of a maser depends exponentially on the population inversion and the velocity-coherent path length, any variation of either will itself result in exponential change of the maser output.

Line narrowing. Exponential gain also amplifies the centre of the line shape (e.g. Lorentzian, etc.) more than the edges or wings. This results in an emission line shape that is much taller but not much wider. This makes the line appear narrower relative to the unamplified line.

Consequences (2)

High brightness. The brightness temperature of a maser is *the temperature a black body* would have if producing the same emission brightness at the wavelength of the maser.

$$T_b = \frac{I_\nu c^2}{2\nu^2 k} \quad \text{where} \quad I_\nu = \frac{2\nu^2 kT}{c^2} \quad \text{in the Rayleigh-Jeans limit of low frequencies}$$

If an object had a temperature of ~109 K it would produce as much 1665-MHz radiation as a strong interstellar OH maser. At 109 K the OH molecule would dissociate (*kT* is greater than the bond energy), so the brightness temperature is not directly indicative of the kinetic temperature of the maser gas but is nevertheless useful in describing maser emission.

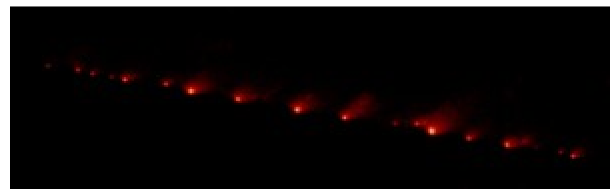
Masers have huge effective temperatures, up to 1e15 K !!

Polarisation. Astronomical masers are often very highly polarised, sometimes 100%. This polarisation is due to some combination of the *Zeeman effect*, *magnetic beaming* of the maser radiation, and *anisotropic pumping* which favours certain magnetic-state transitions.

Maser environments (1): Comets

* small bodies (5-15km diameter) of frozen volatiles (H_2O, CO_2, NH_3, CH_4) embedded in a crusty silicate filler.
* an approach to the Sun causes the vaporization of these molecules

1. The impact of comet *Shoemaker-Levy 9* with Jupiter in 1994 resulted in *maser emission at 22 GHz* from the water molecule.



2. Ultraviolet light from the sun breaks down some H_2O molecules forming OH molecules that can mase. In 1997, 1667-MHz maser emission from the OH molecule was observed from comet Hale-Bopp.

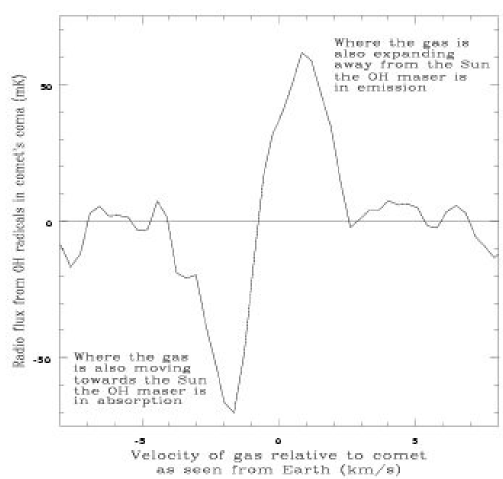


Fig. 3. 1667 MHz OH maser emission from Comet Hale-Bopp on 28th March 1997. The comet was observed with the Lovell telescope. 0 km s^{-1} is the velocity of the core of the comet as seen from Earth.

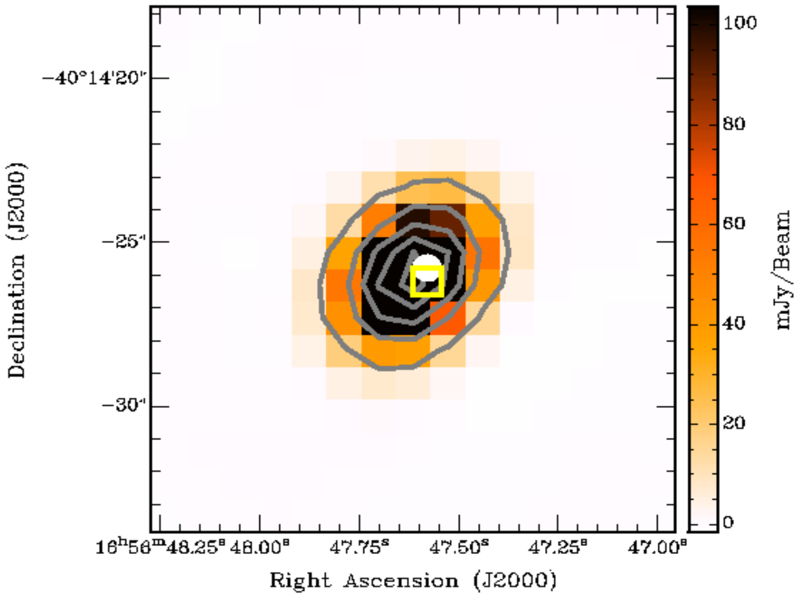
Maser environments (2): star-forming regions

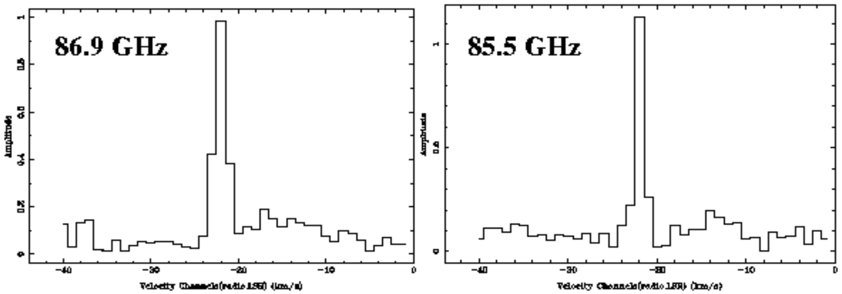
6.7 and 12.2-GHz methanol masers had been recognized as excellent tracers of the physical conditions in massive star-forming regions, at scales from 1 to 1000 AU (1 milliarcsecond to 1 arcsecond at 1 kpc)

VLBI observations have shown that 6.7 and 12.2-GHz methanol masers arise within 3000 AU around the massive stellar object and that the masing regions have linear dimension from 1 to 100 AU.

As masers require very specific density and temperature to switch on, their observation at high resolution would reveal the nature of the physical conditions in the inner part of the protostellar envelope.

Methanol masers also exist at higher frequencies in the 3-mm range. For instance, in G345.01+1.79, a *massive star-forming region*, exhibits strong methanol emission at 6.7, 12.2, 85.5, 86.6, 86.9, 107.0, 108.8 and 156.6 GHz. The millimetre emission lines have been interpreted as maser features based on their narrow line-widths.

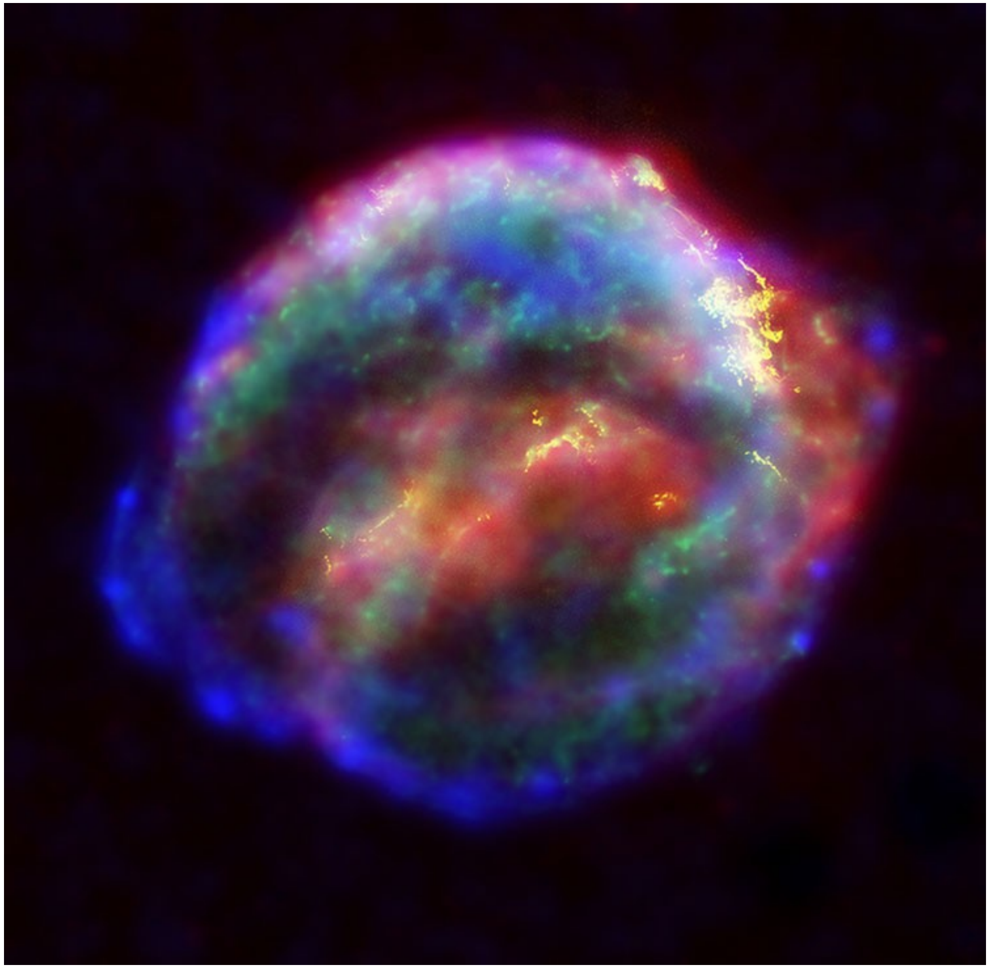




Methanol masers in G345.01+1.79. (a) Positions of the 6.7 and 12.2-GHz masers (white circle) and of the 85.5 and 86.9-GHz methanol masers (yellow square) overlaid on the radio continuum emission (colour scale and grey contours). The ATCA 3-mm maser spectra are shown at the bottom.

Maser environments (3): SNR

The 1720 MHz maser transition of the OH molecule is known to be associated with supernova remnants that interact with molecular clouds.



Maser environments (4): atmospheres of plantes and stars

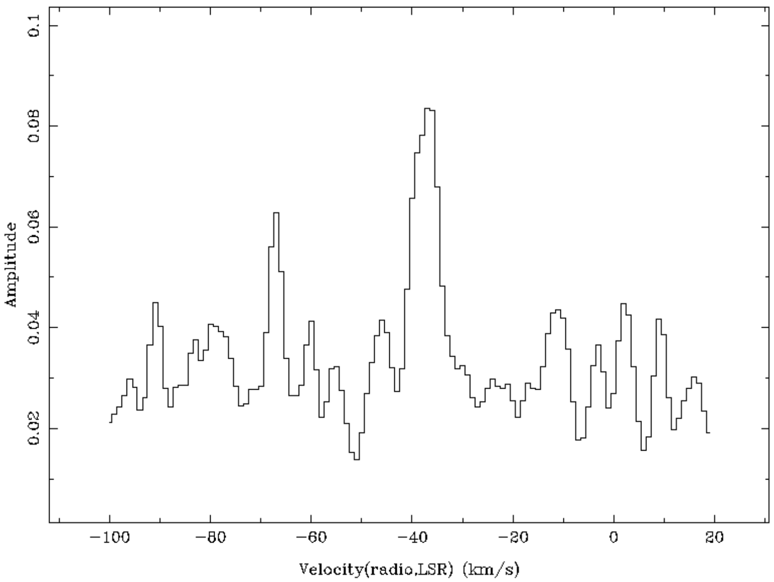
It is predicted that masers exist in the atmospheres of giant planets. If so, such masers would be highly variable due to planetary rotation.

22-GHz water-maser emission has been reported coming from Jupiter induced by the Shoemaker-Levy comet collision (Cosmovici *et alii* 1996) and more recently from several exoplanet host stars (Cosmovici *et alii* 2002). However, null results have also been reported for five exoplanet host stars of which Upsilon Andromedae and Epsilon Eridani were thought to emit water-maser emission.

The mechanisms that might generate 22-GHz water-maser emission include *cometary impacts* in atmospheres of giant planets (maily considered).

Detection made toward HD47536, a K1III giant star located at 123 pc which is probably orbited by a giant planet:

* detected line is narrow and peaks at a radial velocity of 37 km/s, which would correspond to nearly the maximum Keplerian velocity of the candidate planet around HD47356



Possible detection of a 22.2-GHz water-vapour maser in HD47536; a K giant star with a 5-9 MJ companion

Maser environments (5): extragalactic sources

Masers observed from *distant galaxies* generally arise in wholly different conditions.

Some galaxies possess central black holes with a disk of molecular material (about 0.5 parsec in size).

Excitations of these molecules in the disk (or in a jet) can result in megamasers with large luminosities.
Masers which are known to exist in these conditions:

* hydroxyl
* water
* formaldehyde

Megamasers (1)

Galaxies that exhibit megamaser activity are:

* all active galaxies (AGN) with enormous IR luminosities ($L_{IR} > 1e11\ L_{O}$)
* very rich in molecular gas compared to ordinary spiral galaxies

A chance of finding OH megamasing increases with L_{IR} and reaches 50% for galaxies with $L_{IR} > 1e12\ L_{O}$.

* characterized by steep spectra in the mid-IR and sloping in the far-IR
* dust absorbing high-energy radiation and re-emitting it in the infrared is the source of the high L_{IR} values

Galaxies have been characterised as:

* Seyfert 2 or LINERS in 20 cases
* starburst nuclei in 13 cases
* Seyfert 1 in two cases

A large number of these galaxies are in the process of mergers, collisions or gravitational interactions.

Starburst activity is most probably caused by tidal forces acting on molecular clouds in the galaxies, causing rapid star formation.

Megamaser galaxies form a class of *low redshift objects* in a state of rapid evolution - probably the megamaser phase is the initial phase of galactic collisions.

Megamasers (2)

Megamaser emission can be contrasted to that of ordinary astronomical masers:

* Megamaser amplification factors are very low: often the radiation is not even doubled in intensity on passing through a megamaser, and so the line narrowing effect is very small

* Megamasers emission does not have narrow lines: megamasers have huge velocity ranges of hundreds of km/s in them, and so Doppler shifts stretch out the lines so that they are very broad

* Megamasers are not bright relative to galactic masers (though of course are still much brighter than any black body of similar temperature)

* Megamaser emission is not polarised.

Megamasers (3)

Megamaser emission of NGC 4258 (K.Y. 2005)

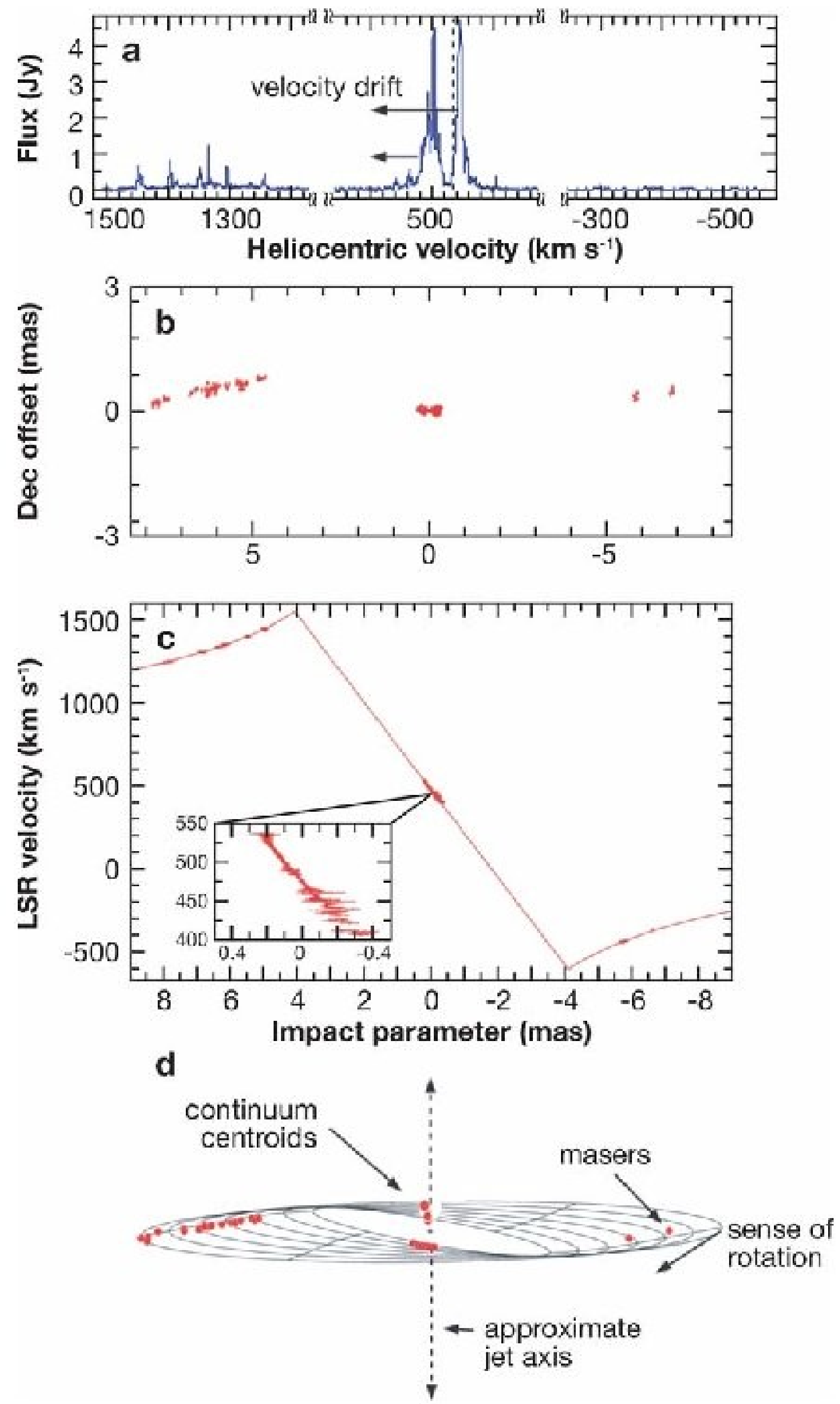
* archetypical curcumnuclear water maser
* rotating disk model

Combination of the high-brightness temperature of circumnuclear water maser emisstion + high-angular resolution of VLBI => allowed for probing of NGC 4258 at 7 Mpc with ~300 micro-as

* Keplerian rotation curve defines a spherical distribution of mass of 3.7e7 within 0.13 pc of the center implying the average mass density of 2e25 g/cm

* if the thinkness of disk = maser source & disk is under hydrostatic equilibrium vertically, then $H/R=c_s/v_p < 0.0025$ (v_p – Kep rotational speed). The value of H implies $c_s < 2.5$ km/s This suggests gas T<1000 K if cs is thermal sound speed.

** excitation of H_20 maser levels requires T of gas to be > 300 K



Megamasers (4)

Emission of Circinus water maser

* maser emission appears to trace an edge-on warped disk
  between the radi of 0.1 pc and 0.4 pc
* as well as wide-angle outflow that extends up to ~1 pc
  from the center
* maximum rotation velocity of the disk is 260 km/s
* what idicates on enclosed mass within 0.1 pc ~1.7e7 M_{sun}