12. Megamasers

Maser sources in the ISM of galaxies

amplification of ISM molecular line radiation at microwave and radio wavelengths

classical maser lines

OH at $\lambda = 18\text{cm}$
$\text{H}_2\text{O}$ at $\lambda = 1.35\text{cm}$

Milky Way:

- masers in immediate neighborhood of young stellar objects or circumstellar envelopes of evolved stars

- isotropic luminosities up to $1 \, L_{\odot}$ (integrated over all lines) or up to $0.1 \, L_{\odot}$ in one line (example star formation region W49N)
External Galaxies:

- H$_2$O maser
  in high density molecular gas located in circumnuclear disks
  within parsecs of AGN cores (Seyfert 2, LINER, spirals, ellipticals)

- OH maser
  within 100 pc of nuclear starburst regions

- isotropic luminosities $\sim 10^2 - 10^4$ L$_{\text{sun}} \rightarrow 10^6$ brighter than MW maser
  $\Rightarrow$ Megamaser

- archetype megamaser galaxy is NGC 4258 at 7.6 Mpc

- most distant megamaser detected at red shift $z = 0.66$

Megamaser are potential distance indicators in the Hubble flow

Herrnstein, J.R. et al., 1999, Nature 400, 539
Maser mechanism

most likely process:
- collisional excitation from below (symbolic level a) to upper (symbolic) level b
- spontaneous transitions from b downwards overpopulate level u relative to level l
- level inversion
  \[ \kappa_\nu = \frac{h\nu}{4\pi} \phi(\nu) B_{lu} \left( n_l - \frac{g_l}{g_u} n_u \right) \]
  \[ \Rightarrow \text{line absorption coefficient negative} \]
  \[ \Rightarrow \text{line emission exponentially amplified} \]
  \[ \Rightarrow \text{line emission exponentially amplified by stimulated emission} \]

\[ I^0_\nu \]
\[ I_\nu = I^0_\nu e^{-\int_0^L \kappa_\nu dL} \]

note: exponent is positive exponential amplification
Rotational Transitions of $\text{H}_2\text{O}$ (An Asymmetric Top molecule)

$J_{K+K-}$

$E(6_{16})/k = 640 \text{ K}$

$6_{16}-5_{23}$:

$\lambda = 1.35 \text{ cm}$

$\nu = 22.235 \text{ GHz}$
“Maser Galaxy” distance accurate to 3%
Humphreys et al., 2013

New anchor galaxy of extragalactic distance scale using PLR of Cepheids
Riess et al., 2011

NGC 4258  7.6 Mpc
NGC 4258 - observations

1. spectrum at 1.35 cm of the central region

- strong $H_2O$ emissions lines

- three radial velocity systems
  
  $v_{\text{rad}} \sim -470 \text{ km/s}$ (systemic velocity)

  and

  $v_{\text{rad}} \sim -470 \pm 1000 \text{ km/s}$ (blue and red shifted)

- for each systems many different components

- obvious interpretation: we look almost edge on at a circumnuclear disk which is rotating with $\sim 1000 \text{ km/s}$
Strong nuclear water maser at 22 GHz

NGC 4258 - spectrum at 1.35 cm

\[ v_{\text{sys}} \pm 1000 \text{ km s}^{-1} \]

GBT (Modjaz et al. 2005)
2. VLBA imaging and spectroscopy of NGC 4258

VLBA: Angular resolution = 200 µas (0.006 pc at ~ 7.0 Mpc)

Spectral resolution < 1 kms⁻¹

MIAPP, 28 May 2014
2. VLBA imaging and spectroscopy

- Individual masers resolved and $v_{\text{rad}}$ assigned to individual components
- Objects in front of AGN have $v_{\text{rad}} \sim -470 \text{ km/s}$ (systemic velocity), the inclination angle relative to AGN is $i \sim 82^\circ$
- Objects at the edges have $v_{\text{rad}} \sim -470 \pm 1000 \text{ km/s}$ (blue and red shifted)
- A rotating Keplerian disk provides a perfect fit to each individually observed components of the three radial velocity systems with an accuracy better than 1%
This Dataset: 18 epochs

1 mas @ 7.2 Mpc \rightarrow 0.04 pc

Argon, Greenhill, Reid, Moran & Humphreys (2007)
VLBA + VLA +EFLS

Humphreys, 2014, MIAPP WS
Red-shifted emission

Humphreys, 2014, MIAPP WS

Argon et al. (2007)
Systemic Maser Emission

Humphreys, 2014, MIAPP WS

Low-velocity average 1997–2000

Low-velocity

2.5 Jy
250 mJy
25 mJy
Blue-shifted Emission

Blue-shifted average
1997–2000

Flux Density (Jy)
0.03
0.02
0.01

Radio LSR Velocity (km s⁻¹)
-500
-450
-400
-350
-300
-250

Blue-shifted

2.5 Jy
250 mJy
25 mJy

MIAPP, 28 May 2014
Masers probe sub-pc portion of nuclear disk

Almost perfect Keplerian rotation to \( \sim 1\% \)

Miyoshi et al. (1995)
Herrnstein et al. (1999)
more detailed discussion of model will follow later

First detected in GBT observations by Modjaz
3. Time dependence and observed rotational motion

- the individual components of the $v_{\text{rad}} \sim -470 \text{ km/s}$ system in front of the AGN show a common change with time in $v_{\text{rad}}$ and position

- average acceleration $\frac{dv_{\text{rad}}}{dt} = a = 9.3 \text{ km/s/yr}$

- average change of impact parameter position $\frac{d\Theta}{dt} = 31.5 \text{ mas/yr}$

- the $\pm 1000 \text{ km/s}$ components at the edges do not show such a drift

- this can be perfectly understood as the result of Keplerian rotation
Herrnstein et al., 1999
position drift \[ \frac{d\Theta}{dt} = 31.5 \text{ mas/yr} \]
4. A simple model

thin rotating Keplerian disk
- AGN with mass $M$ at center
- maser at angle $\varphi$, radius $R$
- projected angular distance of maser from center (impact parameter) is $\Theta$
- $D$ is distance of galaxy to observer
- projected linear distance of maser from the center is

$$D \Theta = R \cos(\phi)$$

$$\cos(\phi) = \frac{D \Theta}{R}$$

$$v_{rot} = \left(2G \frac{M}{R}\right)^{\frac{1}{2}}$$

Keplerian velocity

observed radial velocity

$$v_{rad} = \cos(\phi) v_{rot}$$
5. Likelihood to detect masers at $\varphi = 0^\circ$ and $90^\circ$

for strong maser amplification one needs a long light path along which Doppler shifts of photons through differential rotational velocity are smaller than a thermal line width

$$\Delta \nu = \nu_0 \frac{\Delta v_{\text{rad}}}{c} \leq \Delta \nu_{\text{th}} = \nu_0 \frac{\Delta v_{\text{th}}}{c}$$

or

$$\Delta v_{\text{rad}} \leq v_{\text{th}} \approx 1 \text{ km/s}$$

The longest coherence lengths are obtained for

- $\varphi = 90^\circ$ (no Doppler shifts)
- and
- $\varphi = 0^\circ$ (smallest gradient of $v_{\text{rad}}$ along light path)
calculation of maser coherence length $\Delta l_c$

\[ v_{\text{rad}} = \cos(\phi) v_{\text{rot}} \]

\[ v_{\text{rot}} = \left(2G\frac{M}{R}\right)^{\frac{1}{2}} \]

\[ \frac{dv_{\text{rad}}}{dl} = \cos(\phi) \frac{dv_{\text{rot}}}{dl} + v_{\text{rot}} \frac{d\cos(\phi)}{dl} \]

\[ \frac{dv_{\text{rot}}}{dl} = -\frac{1}{2} v_{\text{rot}} \frac{1}{R} \frac{dR}{dl} \]

\[ \frac{d\cos(\phi)}{dl} = -\sin(\phi) \frac{d\phi}{dl} \]

\[ \left| \frac{dv_{\text{rad}}}{dl} \right| = v_{\text{rot}} \left( \sin(\phi) \left( \frac{d\phi}{dl} \right) + \frac{1}{2R} \cos(\phi) \frac{dR}{dl} \right) \quad (1) \]
\[(R + dR)^2 = (R\cos(\phi))^2 + (R\sin(\phi) + dl)^2\]

\[2RdR = 2R\sin(\phi)dl + dl^2\]

\[dR \approx dl \left( \sin(\phi) + \frac{dl}{2R} \right) \quad (2)\]

Applying the law of sines and noting that the angle between \(v_{\text{rot}}\) and \(v_{\text{rad}}\) is \(\phi\)

\[\frac{\sin(d\phi)}{dl} = \frac{\sin(\frac{\pi}{2} + \phi)}{R + dr} = \frac{\cos(\phi)}{R + dr}\]

\[d\phi \approx \frac{\cos(\phi)}{R} dl \quad (3)\]

Combining (2) and (3) with (1) we obtain...
\[
\frac{dv_{rad}}{dl} = \frac{1}{R} v_{rot} \cos(\phi) \left( \frac{3}{2} \sin(\phi) + \frac{dl}{4R} \right) \quad \text{or}
\]

\[
4R^2 \frac{\Delta v_{rad}}{v_{rot}} = \Delta l_c \cos(\phi) \left( 4R \frac{3}{2} \sin(\phi) + \Delta l_c \right) \quad (4)
\]

For the tangential angle \( \varphi = 0^\circ \) we obtain from (4) and we then re-write (4) as

\[
\left( \frac{\Delta l_c}{\Delta l_0} \right)^2 + 3 \left( \frac{v_{rot}}{\Delta v_{rad}} \right)^{\frac{1}{2}} \sin(\phi) \frac{\Delta l_c}{\Delta l_0} - \frac{1}{\cos(\phi)} = 0
\]

which has the solution

\[
\frac{\Delta l_c}{\Delta l_0} = -\frac{3}{2} \left( \frac{v_{rot}}{\Delta v_{rad}} \right)^{\frac{1}{2}} \sin(\phi) + \sqrt{\frac{9}{4} \frac{v_{rot}}{\Delta v_{rad}} \sin^2(\phi) + \frac{1}{\cos(\phi)}} \quad (6)
\]
with \( v_{\text{rot}} \approx 1000 \text{ km/s} \) and \( \Delta v_{\text{rad}} \approx 1 \text{ km/s} \)

\[
\frac{\Delta l_c}{\Delta l_0} = -\frac{3}{2} \left( \frac{v_{\text{rot}}}{\Delta v_{\text{rad}}} \right)^{\frac{1}{2}} \sin(\phi) + \sqrt{\frac{9}{4} \frac{v_{\text{rot}}}{\Delta v_{\text{rad}}} \sin^2(\phi)} + \frac{1}{\cos(\phi)}
\]

the solution varies dramatically as soon as \( \sin(\phi) \neq 0 \), as shown in the figure on the next page.

\( \frac{\Delta l_c}{\Delta l_0} \) is different from zero only at \( \phi = 0^\circ \) and \( 90^\circ \).

For \( v_{\text{rot}} \approx 1000 \text{ km/s} \) and \( \Delta v_{\text{rad}} \approx 1 \text{ km/s} \) we have \( \Delta l_0 = 0.06R \).

For \( R = 0.2 \text{ pc} \) this corresponds to \( 3.7 \times 10^{16} \text{ cm} \).

This explains why we see masers mostly at \( \phi = 0^\circ \) and \( 90^\circ \).
6. Discussion of the model and distance

\[ v_{\text{rot}} = \left( \frac{2G M}{R} \right)^{\frac{1}{2}} \quad \cos(\phi) = \frac{D \Theta}{R} \]

\[ v_{\text{rad}} = \cos(\phi) v_{\text{rot}} \]

In front of AGN with \( \varphi \approx 90^\circ \) we see the systemic components which have slightly different \( \cos \varphi \) according to their different \( \Theta \).

\[ v_{\text{rad}} = \frac{D}{R} v_{\text{rot}} \Theta \]

\[ b = \frac{D}{R} v_{\text{rot}} \]

\[ \text{(7)} \]

\( \rightarrow \) linear behaviour in \( v_{\text{rad}} \) vs impact parameter figure. Obviously, the components are at roughly the same radius.

The average slope \( b \) can be measured from this figure.
Masers probe sub-pc portion of nuclear disk

Almost perfect Keplerian rotation to ~ 1%

Miyoshi et al. (1995)
Herrnstein et al. (1999)
for these components we can also use the observed drifts in $v_{\text{rad}}$ and $\Theta$

$$\frac{dv_{\text{rad}}}{dt} = a = v_{\text{rot}} \frac{d}{dt} \cos(\phi) = -v_{\text{rot}} \sin(\phi) \frac{d\phi}{dt}$$

the $\sin(\varphi)$ factor explains why no drift at $\varphi = 0^\circ$.

For $\varphi \sim 90^\circ$, $\sin(\varphi) \sim 1$ and with

$$\phi(t) = \omega t \quad \omega = \frac{v_{\text{rot}}}{R}$$

we obtain

$$a = \frac{v_{\text{rot}}^2}{R} \quad (8)$$

the spatial drift is the change of $\Theta = \frac{R}{D} \cos(\phi)$ with time

$$\frac{d\Theta}{dt} = -\frac{R}{D} \sin(\phi) \frac{d\phi}{dt} = -\frac{R}{D} \sin(\phi) \frac{v_{\text{rot}}}{R}$$

and for $\varphi \sim 90^\circ$, $\sin(\varphi) \sim 1$

$$\frac{d\Theta}{dt} = \frac{v_{\text{rot}}}{D} \quad (9).$$

The measurements (7), (8), (9) already yield $R$, $D$, $v_{\text{rot}}$ from the systemic components.
In addition, we can use the \( v_{\text{rad}} \) shifted components at \( \varphi \sim 0^\circ \) and 180°. We start again with

\[
v_{\text{rad}} = \cos(\varphi)v_{\text{rot}}
\]

\[
\cos(\varphi) = \frac{D\Theta}{R}
\]

\[
v_{\text{rot}} = \left(2G\frac{M}{R}\right)^{\frac{1}{2}}
\]

Using \( \frac{1}{R} = \frac{\cos(\varphi)}{D\Theta} \), we obtain

\[
v_{\text{rad}} = \cos(\varphi)^{\frac{3}{2}} \left(2G\frac{M}{D}\right)^{\frac{1}{2}} \frac{1}{\Theta^{\frac{1}{2}}} \tag{10}
\]

this is the fit curve in the \( v_{\text{rad}} \) vs impact parameter figure.

All \( v_{\text{rad}} \) shifted maser components are on one curve \( \rightarrow \) same \( \cos \varphi \) for all.

Following section 5, we adopt \( \varphi = 0^\circ \) and 180°.

(10) yields \( M/D \) which can be used for distance together with (7), (8), (9).
fit residuals smaller than 1%!!

First detected in GBT observations by Modjaz
first detailed distance determination by

Herrnstein, J.R. et al., 1999, Nature 400, 539

gave $D = 7.2 \pm 0.5$ Mpc

Improved data with longer time base line and refined fitting algorithms assuming a warped confocal elliptical disk and differential precession by


resulted in

$$D = 7.6 \pm 0.17 \pm 0.15 \text{ Mpc}$$

fitting systematic errors

This is a 3% accuracy and the most accurate distance to a galaxy outside the Local Group.

The mass of the AGN black hole is $(4.0 \pm 0.09) \times 10^7 M_{\text{sun}}$. 
Search for Megamasers in the Hubble Flow

Megamasaser Cosmology Project (MCP)

NRAO Key Project (Pl: Braatz) to determine $H_0$ by measuring geometric distances with an accuracy of $\sim10\%$ to $\sim10$ galaxies in the Hubble Flow

Braatz, Condon, Constantin, Greene, Hao, Henkel, Impellizzeri, Kuo, Lo, Reid, et al.
Goal: Direct $H_0$ Measurement

- Water masers in AGN have been detected well into the Hubble Flow
  - distances out to $\sim 200$ Mpc
- Direct estimation of $H_0$
- Systematic uncertainties in individual disk models not likely to be correlated
  - Uncertainty in $H_0$ scales as $\sigma_{H_0}/H_0 \approx N^{-0.5}(\sigma_D/D)$
- Broad distribution on sky needed to reduce impact of large scale flows
  - Even after correction from models of cosmic velocity field
The Megamaser in UGC 3789

Braatz & Gugliucci 2008; Reid et al. 2009, 2013
Humphreys, 2014, MIAPP WS

UGC 3789

Reid et al. (2013)
UGC 3789
Reid et al. (2013)

D = 49.6 ± 5.1 Mpc
$H_0 = 68.9 \pm 7.1 \, \text{km s}^{-1}\text{Mpc}^{-1}$
10%
NGC 6264

Discovery: Kondratko et al. 2006
Map: Kuo et al. 2011
NGC 6264
Kuo et al. (2013)

D = 144 ± 19 Mpc
Hₐ = 68 ± 9 km s⁻¹ Mpc⁻¹
13%
Cepheids
Distance Ladder

0 Mpc  50 Mpc  100 Mpc  150 Mpc

One geometric method covers all scales out to the Hubble flow and the largest structures
Challenge of Distant Maser Galaxies

Henkel et al. (2012)