A pair of jets protrude outwards in near-perfect symmetry in this image of HH 212, taken by ESO's already decommissioned Infrared Spectrometer And Array Camera (ISAAC). The object lies in the constellation of Orion in a dense molecular star-forming region, not far from the famous Horsehead Nebula. In regions like this, clouds of dust and gas collapse under the force of gravity, spinning faster and faster and becoming hotter and hotter until a young star ignites at the cloud's centre. Any leftover material swirling around the newborn protostar comes together to form an accretion disc that will, under the right circumstances, eventually evolve to form the base material for the creation of planets, asteroids and comets. Although this process is still not fully understood, it is common that a protostar and its accretion disc, as seen here edge-on, are the cause of the jets in this image. The star at the centre of HH 212 is indeed a very young star, at only a few thousand years old. Its jets are remarkably symmetric, with several knots appearing at relatively stable intervals. This stability suggests that the jet pulses vary quite regularly, and over a short timescale — maybe even as short as 30 years! Further out from the centre, large bow shocks spread out into interstellar space, caused by ejected gas colliding with dust and gas at speeds of several hundred kilometres per second.

Further readings:

- Anglada et al., http://pos.sissa.it/archive/conferences/215/121/AASKA14_121.pdf
- McKee & Ostriker, 2007, ARAA, 45, 565-687
- Shang et al., Protostars & Planets V, pp. 261-276
Young Stellar Objects

Where do they form?
- Bok globules (low mass star forming regions)
- GMC
Star forming regions

Ingredients:
CNM (dust & molecules) + seeds (perturbations)

Prescription:
➢ Gravitational collapse & (slow) accretion
➢ Bipolar outflows carry away angular momentum
➢ Start as molecular outflows
➢ Then become atomic & develop jets
➢ Influence / interaction with the parent cloud
➢ Radiation from line emission (molecules) & continuum when shocks set up (non – t!) and/or massive stars ionize surrounding medium
Starting model: spherical, static (self-gravitating, no rotation), homogeneous, isothermal cloud with no B field

Gravitational (dynamical) collapse: **INSIDE – OUT**

Gravitational collapse takes place if the size of the cloud exceeds the Jeans' Length $J_L$

$$J_L = \sqrt{\frac{15kT}{4\pi G m \rho}}$$

A cloud that is smaller than its Jeans length will not have sufficient gravity to overcome the repulsive gas pressure forces and condense to form a star.
Starting model: spherical, static (self-gravitating, no rotation), homogeneous, isothermal cloud with no B field

Gravitational (dynamical) collapse: **INSIDE – OUT**

a more realistic case:

1. a relatively uniform cloud (molecular gas, dust) with some rotation and B field start to collapse

2. accretion to the condensed object is more efficient in a plane perpendicular to the rotation axis; as the mass assembly proceeds the rotation of the whole structure speeds up

3. the main accretion phase takes place from an equatorial disk; rotation has increased, and needs to be slowed down; outflows and jets of matter are created and angular momentum is brought away from the system
Fragmentation of a molecular cloud into a number of gravitationally bound cores initially supported by a combination of thermal, magnetic and turbulent pressures.

**Brief initial phase:**

- Gravitational energy released is mostly radiated away mainly by dust.
- The fragment is isothermal.
- Strong central condensation $\rho (r) \sim r^{-2}$.

Formation of a hydrostatic (adiabatic) proto-stellar object at the centre of each condensation.
Main accretion phase:

- Mass from the in-falling envelope deposited onto an accretion disk, progressively warming up
- Angular momentum has to be dissipated, otherwise the rotation will get to the breakup (i.e. match the escape velocity from the body surface) of the central object preventing any further accretion

\[
v_r = \omega \cdot r \leq v_{esc} = \sqrt{\frac{2GM}{r}}
\]

⇒ will get to the breakup (i.e. match the escape velocity from the body surface) of the central object preventing any further accretion
Young Stellar objects Class 0-I-II-III

Class 0:
Main Acceleration phase?
Age ≤ 10^5 years
M ~ 0.5 M_☉

Class I:
Late accretion phase?
Age ~ 10^5 years
M ~ 0.1 M_☉

Class II:
Optically thick disk
Age ≤ 10^6 years
<M_{disk}> ~ 0.01 M_☉

Class III:
Optically thin disk
Age ≥ 10^6 years
<M_{disk}> ~ 0.003 M_☉
Planetary System
Young Stellar objects Class 0-I-II-III

Class 0: Cold condensations of in-falling molecular gas
Hydrostatic low-luminosity proto-stellar object
Thermal emission mostly in the mm-sub-mm region (ALMA) by cold dust (< 20°K)
Detections in the radio at cm-wavelengths sensitive to the presence of a proto-stellar core
Responsible of a jet/collimated wind
Class I: protostar still enshrouded by optically thick material
Emission from collimated thermal winds/jets ionized by neutral winds impacting the ambient medium
(with polarization!)
Aligned to the molecular outflows
Young Stellar objects Class 0-I-II-III

Class II: TTauri phase: optical (reddened!) emission starts to come out along with a weak outflow and a wind

Birth line for pre-main sequence stars

Class II:
Optically thick disk
Age \leq 10^6 \text{ years}
\langle M_{\text{disk}} \rangle \sim 0.01 M_\odot

Class III:
Optically thin disk
Age \geq 10^6 \text{ years}
\langle M_{\text{disk}} \rangle \sim 0.003 M_\odot
Planetary System
Class III: Evolved T Tauri, the star approaches the main sequence.
Accretion substantially halted, proto-planetary disks may be present.

Class III:
Optically thin disk
Age $\geq 10^6$ years
$<M_{\text{disk}}>$ $\sim 0.003$ $M_\odot$
Planetary System
Young Stellar objects: Bipolar (molecular) outflows

Outflows: Snell+, 1980

- Stellar Wind (100-200 Km s⁻¹)
- Accretion Disk
- Expanding Shell (≈ 50 Km s⁻¹)
- Herbig-Haro Objects

Expansion bubble

Line emission is Doppler shifted (broad)

GMC

GMC+ expanding bubble

Outflow launching region (SGS model)

Accretion disk

Sink particle

$S_{\text{sink}}$

$\theta_{\text{out}}$

$r_{\text{out}}$

$r_{\text{sink}}$

Bipolar outflows: Molecular stage

➢ Pudritz (1986): various components at work

➢ Their relative importance determines the protostellar class

➢ N.B. Consider the relative scales
Young Stellar objects: the role of radio emission

Outflows & Jets: model vs. observation
Various molecules trace different cloud components with various optical depths, densities, etc.

All this generates a multilayer model of the SFR and of its outflow-jet structure.

In SFR where multiple cores are developing their gravitational instability, the mutual interaction may generate new perturbations/instabilities leading to further collapses.
Young Stellar objects: various ingredients

Low velocity molecular gas (white contours)

High velocity molecular gas (white contours)
Young Stellar Objects: various ingredients

Interaction between outflows
Young Stellar Objects: Herbig – Haro objects

Spectacular (thanks HST!) beacons of star formation: HH901 & HH 902
However, lots of dust & cold gas absorb many photons!
Young Stellar Objects: Herbig – Haro objects

Herbig – Haro objects: spectacular signature of SF

George Herbig
1920 - 2013

Guillermo Haro
1913 - 1988
Radio emission: Effective tool to investigate the earliest phases (the dense core region is still optically thick!)

- The main emission mechanism of the radio emission is thermal bremsstrahlung (shock-ionized plasma) of a cooling plasma, created by outflow/jet heating of the ambient medium.

- In a few objects, also non-thermal emission from a population of relativistic electrons has been detected.

- The cartoon shown above imply also (optical) line emission of recombination of cooling elements (ionized / neutral). Protostars with optical jets are known as Herbig-Haro objects.
Young Stellar objects: the role of radio emission

The kinetic energy of the ejected material can be transferred to produce a population inversion of the impacted ambient, and generate maser emission.

Masers in SFR are ubiquitous and variable point-like sources. Many species.
Bipolar outflows: atomic/ionized stage

Thermal & Non-Thermal Jets:

The spectrum is the key for determining which of the two mechanisms is at work.

Surcis +, 2009: Positions of methanol (o) and water (Δ) masers superimposed on 1.3cm continuum contour map of the VLA 1 thermal jet and VLA 2 (Torrelles +, 1997). The red segments indicate linear polarization vectors (40mas = 1%). Arrows show the direction of the bipolar outflow (66d) and the parallel dashed lines the B field lines (73 ± 10d) as derived from the linear polarization.
Bipolar outflows: atomic stage

Velocity measurements

More movies at http://sparky.rice.edu/movies.html

Star as position reference

Herbig-Haro object

Polar jet

Accretion disk

Observed Radial Velocity Shift

-12.5 0.0 12.5

Velocity (km/s)
Young Stellar objects: the role of radio emission

Effective tool to investigate the earliest phases (the dense core region is still optically thick!)

- The main emission mechanism is thermal bremsstrahlung (shock-ionized plasma)
Young Stellar objects: the role of radio emission

Similarities with radio galaxies?

HH 1-2 Protostellar jet

Cygnus A Extragalactic jet

Optical

Radio

~0.2 pc

~100 kpc
The radio emission traces the base of the jets, where other emission is optically thick: HH 1-2 is a low mass object.
Young Stellar objects: the role of radio emission

Large number of known YSOs, nearby and lot of information can be obtained from observations at different wavelengths

- **Optical & IR** → Temperature, density, mass
  partially obscured, line (optical) and continuum (IR) emission

- **Radio** → ionized gas, base of the jet, velocity
  (mostly) optically thin, continuum emission, quite weak (mJy level)
  (maser emission in local high brightness spots!)

- **mm/submm** → Disk, molecular outflow
  wealth of molecular lines and dust continuum

Magnetic field very difficult to observe, specially in the jet. We do not know very much about it since the jet is weak and different from those typically found in AGN
Magnetic field detected via polarization of radio emission
Signature of synchrotron emission, with a field of 200 μG in HH 80-81 (Carrasco-Gonzalez et al. 2010)
Young Stellar objects: the role of radio emission

Summary (?) of Thermal jets:
Collimated outflows present in YSO from O-type to brown dwarf proto-stars (disk-jet scenario)

1. Often exhibit a central weak cm emission source
2. Resolved on the sub-arcsec scale, elongated in the same p.a. of the large scale outflow and trace the region where the outflow is originated
3. The spectrum is flattish of slightly inverted, thermal origin
4. Found in all stages of star formation, from class 0 onwards
5. Model of thermal jets in Reynolds (1986) from which some parameters can be inferred from observations

\[
\begin{align*}
\dot{r} &= 0.56 \left( S_{\text{mJy}} \nu_{10}^{-\alpha_{\text{op}}} \right)^{1/2} \theta_o^{-1/2} \left( \nu_{10\text{m}} \right)^{\alpha_{\text{op}}/2-1} D_{\text{kpc}} \left( T_4 \right)^{-1/2} \left( \sin i \right)^{-1/2} F^{-1/2} \left[ 10^{15} \text{ cm} \right] \\
\dot{M} &= 0.938 v_8 x_o^{-1} \left( \frac{\mu}{m_p} \right) \left( S_{\text{mJy}} \nu_{10}^{-\alpha_{\text{op}}} \right)^{3/4} \left( D_{\text{kpc}} \right)^{3/2} \left( \nu_{10\text{m}} \right)^{-0.45+3\alpha_{\text{op}}/4} \theta_o^{3/4} \left( T_4 \right)^{-0.075} \left( \sin i \right)^{-1/4} F^{-3/4} \left[ 10^{-6} \text{ M}_\odot \right]
\end{align*}
\]

where \( v_8 = \frac{v}{10^8 \text{ cm s}^{-1}} \); \( S_{\text{mJy}} = \) flux density in mJy; \( \nu_{10} = \frac{\nu}{10 \text{ GHz}} \); \( \nu_{\text{m}} = \) peak frequency in 10GHz units;

\( \alpha_{\text{op}} = \) optically thick spectral index; \( T_4 = \) temperature in units of \( 10^4 \text{ K} \); \( F = \) Function of optically thick/thin spix

\( x_o = \) ionization fraction
Young Stellar objects: the role of radio emission

\[ r = 0.56 \left( S_{mJy} \nu_{10}^{-\alpha_{op}} \right)^{1/2} \theta_o^{-1/2} \left( \nu_{10m} \right)^{\alpha_{op}/2 - 1} D_{kpc} \left( T_4 \right)^{-1/2} (\sin i)^{-1/2} F^{-1/2} \left[ 10^{15} \text{ cm} \right] \]

\[ \dot{M} = 0.938 v_8 x_0^{-1} \left( \frac{\mu}{m_p} \right) \left( S_{mJy} \nu_{10}^{-\alpha_{op}} \right)^{3/4} \left( D_{kpc} \right)^{3/2} \left( \nu_{10m} \right)^{-0.45 + 3 \alpha_{op}/4} \theta_o^{3/4} \left( T_4 \right)^{-0.075} (\sin i)^{-1/4} F^{-3/4} \left[ 10^{-6} \text{ M}_\odot \right] \]

where \( v_8 = \frac{v}{10^8 \text{ cm s}^{-1}} \); \( S_{mJy} = \) flux density in mJy ; \( \nu_{10} = \frac{\nu}{10 \text{ GHz}} \); \( \nu_m = \) peak frequency in 10GHz units ;

\( \alpha_{op} = \) optically thick spectral index ; \( T_4 = \) temperature in units of \( 10^4 \text{ K} \); \( F = \) Function of optically thick/thin spix

\[ \dot{M} = 0.938 v_8 x_0^{-1} \left( \frac{\mu}{m_p} \right) \left( S_{mJy} \nu_{10}^{-\alpha_{op}} \right)^{3/4} \left( D_{kpc} \right)^{3/2} \left( \nu_{10m} \right)^{-0.45 + 3 \alpha_{op}/4} \theta_o^{3/4} \left( T_4 \right)^{-0.075} (\sin i)^{-1/4} F^{-3/4} \left[ 10^{-6} \text{ M}_\odot \right] \]

- 5. Model of thermal jets in Reynolds (1986) from which some parameters can be inferred from observations

\[ 5. \text{ Model of thermal jets in Reynolds (1986) from which some parameters can be inferred from observations} \]
Fig. 2.—Schematic core-jet spectrum, showing an example of the mapping between spatial structure in a flow and spectral structure in the integrated radio flux (the source is assumed unresolved). The homogeneous core dominates the emission at high frequencies; descending in frequency, one observes first the inner jet where it is confined (\( \epsilon < 1 \)), then the outer jet where it is free (\( \epsilon = 1 \)). The quoted spectral indices of 0.2 and 0.6 could be achieved with a variety of source gradients as described in the text.
Effective tool to investigate the earliest phases (the dense core region is still optically thick!)

1. YSO jets (non-relativistics) are morphologically very similar to relativistic jets.

2. Magnetic fields are also thought to play a fundamental role in the YSO jet phenomenon, similar to relativistic jets. But magnetic fields are very difficult to observe in YSOs.

3. Radio observations suggested the presence of non-thermal emission in some YSO jets.

4. High sensitive radio observations of HH 80-81 confirmed presence of linearly polarized synchrotron emission in HH 80-81.

5. YSO jets CAN accelerate particles up to relativistic velocities (synchrotron emission)

6. With high sensitive radio observations, we can study the magnetic field in YSO jets in a similar way than in relativistic jets.
The kinetic energy of the ejected material can be transferred to produce a population inversion of the impacted ambient, and generate maser emission.
Young Stellar objects: the role of radio emission

Cartoon of the inner region in low/high mass objects: stratification of jet/outflows
Young Stellar objects: the role of radio emission

The kinetic energy of the ejected material can be transferred to produce a population inversion of the impacted ambient, and generate maser emission.

Molecules also emit substantial line radiation.
Further readings:

- Reid & Moran, 1981, ARAA, 19, 231-276
- Lo, 2005, ARAA, 43, 625-676
Masers

Occur when LTE does not hold

First detected in the ISM in the '60s

- OH (1965)
- $\text{H}_2\text{O}$ (1969)
- CH$_3$OH (1970)
- SiO (1974)

\[\text{[CH, H}_2\text{CO, NH}_3, \text{HCN]}\]

Found in both SFR (best in HM objects) and in evolved stars (LPV and supergiants, OH/IR stars)

Also mega-masers (1982) are nowadays known

Very small linear and angular size (maser spots, often broadened by interstellar scattering)

Transitions of the fine/hyperfine structure of molecules
Masers

Trace a particular range of densities: $n \sim 10^5 - 10^{11} \, \text{cm}^{-3}$ >> than in ISM even in GMC

$\Rightarrow$ Condensations in the ISM

A source of energy for the inversion of the population is necessary (pumping)

Different conditions/manifestations in SFR and in evolved stars

Interstellar masers: in SFR – associated with ultracompact HII regions, $\text{H}_2\text{O}$ always present likely lasting for $10^5$ years, OH not found in the largest condensations

Circum – stellar masers: in OH/IR associations (evolved stars)

\[
\begin{array}{c}
3 \\
\text{Excitation} \\
2 \\
\text{IRline} \\
1 \\
\end{array}
\]

Regardless its origin, the pumping works like aside
A molecule is excited to 3, than it decays to 2 where $A_{21}$ is very small, i.e. population inversion!!!
## Interstellar Masers

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Wavelength (cm)</th>
<th>$n$ (cm$^{-3}$)</th>
<th>$T$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>18</td>
<td>$10^5 - 10^7$</td>
<td>100-200</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1.35</td>
<td>$10^7 - 10^9$</td>
<td>300-1000</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>0.83</td>
<td>$10^4 - 10^5$</td>
<td>20-100</td>
</tr>
<tr>
<td></td>
<td>4.49</td>
<td>$10^4 - 10^5$</td>
<td>20-100</td>
</tr>
<tr>
<td>SiO</td>
<td>0.35</td>
<td>$10^9 - 10^{10}$</td>
<td>700-1000</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>1.25</td>
<td>$10^4 - 10^5$</td>
<td>60-150</td>
</tr>
<tr>
<td>H$_2$CO</td>
<td>6.3</td>
<td>$10^4 - 10^5$</td>
<td>20-40</td>
</tr>
</tbody>
</table>
Masers: radiative transfer (from Reid & Moran 1981)

Standard radiative transfer equation:
\[
\frac{dI}{dr} = -\kappa I + \varepsilon
\]
where
\[
\kappa = \frac{h\nu}{4\pi\Delta\nu}(n_1-n_2)B_{21}
\]
\[
\varepsilon = \frac{h\nu}{4\pi\Delta\nu}n_2A_{21}
\]

At equilibrium, neglecting spontaneous emission and collisions...
\[
n_2 - n_1 = (n_2 + n_1)\frac{\Delta R}{R}\frac{\Gamma}{\Gamma + 2B_{21}I(\Omega/4\pi)}
\]

where \(\Gamma\) = rate of population redistribution throughout the pump cycle and \(R\) and \(\Delta R\) are sum and difference of the pump rates into masing levels, \(\Omega\) is the beam solid angle of the microwave emission.

Assuming \(\kappa, \varepsilon\) constant (i.e. \(\Gamma \gg 2B_{21}I(\Omega/4\pi)\))

\[
I(r) = I_0 e^{-\kappa r} + \frac{\varepsilon}{K}(1 - e^{-\kappa r})
\]

If the optical depth \(\tau = \kappa r\) is negative, then an exponential amplification occurs!
Masers: radiative transfer (from Tools of Radio Astronomy)

More appropriately:

\[ \frac{dI}{dr} = -\kappa I + \varepsilon \quad \text{where} \]

\[ \kappa = \frac{h \nu}{4 \pi \Delta \nu} (n_1 - n_2) [B_{12} - B_{21}] \]

\[ \varepsilon = \frac{h \nu}{4 \pi \Delta \nu} n_2 A_{21} \]

At equilibrium, neglecting spontaneous emission and collisions...

\[ n_2 - n_1 = (n_2 + n_1) \frac{\Delta R}{R} \frac{\Gamma}{\Gamma + 2 [B_{12} - B_{21}] I(\Omega / 4 \pi)} \]

where \( \Gamma \) = rate of population redistribution throughout the pump cycle and \( R \) and \( \Delta R \) are sum and difference of the pump rates into masing levels, \( \Omega \) is the beam solid angle of the microwave emission.

Assuming \( \kappa, \varepsilon \) constant (i.e. \( \Gamma \gg 2 [B_{12} - B_{21}] I(\Omega / 4 \pi) \))

\[ I(r) = I_0 e^{-\kappa r} + \frac{\varepsilon}{\kappa} (1 - e^{-\kappa r}) \]

If the optical depth \( \tau = \kappa r \) is negative, then an exponential amplification occurs!
Masers: radiative transfer

Standard radiative transfer equation:

\[ I(r) = I_o e^{-\kappa r} + \frac{\varepsilon}{\kappa} (1 - e^{-\kappa r}) \]

can be rewritten in terms of temperature

\[ T_B(r) = (T_{B_o} - T_x) e^{-\kappa r} + T_x \]

where \( T_x \) is the excitation temperature:

\[ \frac{n_2}{n_1} = e^{-\frac{h \nu}{k T_x}} \]

\( T_x \) is < 0 for population inversion

The population inversion is reduced by \( B_{21} \) when \( 2B_{21} I_\Omega / 4 \pi > \Gamma \)

under this condition the maser is saturated and this occurs when

\[ T_s = \frac{h \nu}{2k} \frac{\Gamma}{A_{21}} \frac{4 \pi}{\Omega} \]

 Unsaturated maser:
small changes in the pump \( (\kappa) \) result in dramatic changes in the emission \( \approx e^{\kappa r} \)

Saturated maser:
changes are proportional to \( \kappa r \) less sensitive indicator of pump variations
Water maser: variability in RX Boo as observed with the 32m dish in Medicina (Winnberg et al. 2008)

RX Boo is a 9-11 mag SRV with a mean spectral type of M 7.5 and a period varying between 340 and 400 days (Kukarkin et al. 1971). Olofsson et al. (2002) in their model fit involving several CO transitions estimated a mass-loss rate of \(6 \times 10^{-7} \text{ Msun yr}^{-1}\) and an expansion velocity of 9.3 km s\(^{-1}\), whereas Teyssier et al. (2006), as a result of another model fit, obtained \(2 \times 10^{-7} \text{ Msun yr}^{-1}\) and 7.5 km s\(^{-1}\), respectively.
Interstellar Masers

RX Boo: maser spots as a function of position, intensity and relative velocity
Interstellar Masers

TX Cam: VLBA movie
STAR molecule formation dust formation photochemical reactions

s-process

C/O<1

convective envelope

\( H_2, CO \)

\( V_0, H_2O, CO_2 \)

\( TiO, SiO \)

pulsation

C/O>1

\( HCN, C_3, C_2H_2 \)

2-30 km/s

\( H_2O \) masers

\( OH \) masers

\( OH \rightarrow O + H \)

\( H_2O \rightarrow OH + H \)

circumstellar envelope with stellar wind → ISM

interstellar radiation field

\( HCN \rightarrow CN + H \)

\( CN \rightarrow C + N \)

10^8 10^{13} 10^{14}

r [cm]

10^8 3000 1000

T [K]

10^{16} 10^{18}

100 20

degenerate CO core

H/He burning shell
Interstellar Masers

Variability: red vs. blue
Delay helps in determining the size of the envelope \( D = c \Delta t \)

VLBI measures the angular size, and then the **distance** is obtained!
Typical luminosities reach about 1 (a few) \( L_{\text{sun}} \) at maximum

Masers (OH and \( H_2O \)) have been detected in external galaxies up to \( z=0.265 \) (1.3 Gpc) and \( z=0.66 \) (4 Gpc) respectively.

Their luminosities reach \( 10^6 \) times those of galactic masers and are then termed MEGAMASERS.

\( OH: \) found in the central 100 pc of ULIRGs, i.e. (nuclear) star bursting galaxies

\( H_2O: \) found within parsecs in AGNs (Sy2, Liners, ellipticals)
Strong nuclear water maser at 22 GHz

Megamasers: NGC4258

Single dish Observation

$\nu_{\text{sys}} \pm 1000 \text{ km s}^{-1}$

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

VLBA: Angular resolution = 200 μas (0.006 pc at ~ 7.0 Mpc)
Spectral resolution < 1 kms⁻¹
This Dataset: 18 epochs

1 mas @ 7.2 Mpc → 0.04 pc

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

Low-velocity average 1997-2000

Radio LSR Velocity (km s\(^{-1}\))

Flux Density (Jy)

Low-velocity

2.5 Jy
250 mJy
25 mJy
Megamasers: NGC4258

Red-shifted emission
Megamasers: NGC4258

Blue-shifted Emission

Blue-shifted average 1997–2000

Flux Density (Jy)

Radio LSR Velocity (km s\(^{-1}\))
VLBA imaging and spectroscopy

- individual masers resolved and vrad assigned to individual components
- objects in front of AGN have vrad $\sim -470$ km/s (systemic velocity)
  
  the inclination angle relative to AGN is $i \sim 82^\circ$

- objects at the edges have vrad $\sim -470 \pm 1000$ 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%

BH mass $\sim 4.0 \pm 0.1 \times 10^7 \, M_{\text{SUN}}$

Distance $\sim 7.6 \pm 0.3$ Mpc

http://www.ifa.hawaii.edu/users/kud/teaching_15/12_Megamasers.pdf
Megamasers: NGC4258 - 4.0\pm 0.1 \, M_{\odot}
Interstellar Masers... and beyond

Pumping: Even in case of population inversion, we need that......

There is “velocity coherence” i.e. Masing molecules must be at the same radial velocity within the thermal width along the gain path

Pumping (2)

- Radiative
- Collisional