A pair of jets protrude outwards in near-perfect symmetry in this image of HH 212, in the constellation of Orion in a dense molecular star-forming region, not far from the famous Horsehead Nebula taken by ESO’s Infrared Spectrometer And Array Camera (ISAAC). In regions like this, clouds of dust and gas collapse, ruled by 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 disk that will, under the right circumstances, eventually provide 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, 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 km per second.
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

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

\( \Rightarrow \) 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 \( \leq 10^5 \) years
\( M \sim 0.5 \, M_\odot \)

Class I: 
Late accretion phase?
Age \( \sim 10^5 \) years
\( M \sim 0.1 \, M_\odot \)

Birth line for pre-main sequence stars

Class II: 
Optically thick disk
Age \( \leq 10^6 \) years
\( <M_{\text{disk}} > \sim 0.01 \, M_\odot \)

Class III: 
Optically thin disk
Age \( \geq 10^6 \) years
\( <M_{\text{disk}} > \sim 0.003 \, M_\odot \)
Planetary System
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

\[ <M_{\text{disk}} > \sim 0.003 \, M_\odot \]

Planetary System
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
Class II: T Tauri phase: optical (reddened!) emission starts to come out along with a weak outflow and a wind.
Young Stellar objects Class 0-I-II-III

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

Line emission is Doppler shifted (broad)
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
Young Stellar Objects: various ingredients

- 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

H$_2$ 2.12 μm (colors) + CO J=2–1 V<10 km/s (white) + continuum 1.3 mm (red)

Low velocity molecular gas (white contours)

H$_2$ 2.12 μm (colors) + CO J=2–1 V>10 km/s (white) + continuum 1.3 mm (red)

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
Young Stellar objects: the role of radio emission

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.
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 1.3 cm continuum contour map of the VLA 1 thermal jet and VLA 2 (Torrelles +, 1997). The red segments indicate linear polarization vectors (40 mas = 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

HH 34
[S II]
1000 AU

Observed Radial Velocity Shift

DISK

JET

0.15

Velocity (km/s)

1994.6 UT

Star as position reference

Herbig-Haro object
Polar jet
Accretion disk
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?
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 $\mu$G 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 (quite rare) to brown dwarf (very common) 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, sometimes complex, 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

\[
\begin{align*}
   r &= 0.56 \left( \frac{S_{\text{mJy}}}{\nu_{10}^{\alpha_{op}}} \right)^{1/2} \frac{\nu_{10}}{\theta_{o}}^{1/2} \left( \frac{\nu_{10}}{\nu_{10m}} \right)^{\alpha_{op}/2-1} D_{kpc} \left( \frac{T}{10^4} \right)^{-1/2} (\sin i)^{-1/2} F^{-1/2} \quad [10^{15} \text{cm}] \\
   \dot{M} &= 0.938 \nu_{8} \frac{x_{o}}{m_{p}} \left( \frac{\nu}{10^8 \text{cm} \text{s}^{-1}} \right)^{-3/4} \left( \frac{S_{\text{mJy}}}{\nu_{10}^{\alpha_{op}}} \right)^{3/4} \left( \frac{D_{kpc}}{D_{kpc}} \right)^{3/2} \left( \frac{\nu_{10m}}{\nu_{10}} \right)^{-0.45 + 3 \alpha_{op}/4} \left( \frac{\theta_{o}}{\theta_{o}} \right)^{3/4} \left( \frac{T}{10^4} \right)^{-0.075} (\sin i)^{-1/4} F^{-3/4} \quad [10^{-6} \text{M}_\odot] \\
\end{align*}
\]

where \( \nu_{8} = \frac{\nu}{10^8 \text{cm} \text{s}^{-1}} \); \( S_{\text{mJy}} = \text{flux density in mJy} \); \( \nu_{10} = \frac{\nu}{10 \text{GHz}} \); \( \nu_{m} = \text{peak frequency in 10GHz units} \); \( \alpha_{op} = \text{optically thick spectral index} \); \( T_{4} = \text{temperature in units of } 10^{4} \text{K} \); \( F = \text{Function of optically thick/thin spix} \); \( x_{o} = \text{ionization fraction} \)
Young Stellar objects: the role of radio emission

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

\[ \dot{M} = 0.938 \nu_8 \chi_o^{-1} \left( \frac{\mu}{m_p} \right) \left( S_{\text{mJy}} \nu_{10}^{-\alpha_{\text{op}}} \right)^{3/4} \left( D_{\text{kpc}} \right)^{3/2} \left( \nu_{10m} \right)^{-0.45 + 3 \alpha_{\text{op}}/4} \theta_o^{3/4} \left( T_4 \right)^{-0.075} \left( \sin i \right)^{-1/4} F^{-3/4} \]  \[ \text{[10}^{-6} \text{M}\odot] \]

where \( \nu_8 = \frac{\nu}{10^8 \text{ cm s}^{-1}} \); \( S_{\text{mJy}} \) = flux density in mJy; \( \nu_{10} = \frac{\nu}{10 \text{ GHz}} \); \( \nu_{10m} \) = peak frequency in 10GHz units; indeed, \( \nu_{10m} \) is the frequency at which the extrapolations of asymptotically optically thick and thin spectra meet.

\( \alpha_{\text{op}} \) = optically thick spectral index; \( T_4 \) = temperature in units of \( 10^0 K \); \( F \) = Function of optically thick/thin spix

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

- \( r_o \) = core (collimation) radius

- \( \dot{M} \) is the outflow mass loss rate

See Reynolds (1986) for a proper description
Young Stellar objects: the role of radio emission

Combination of
1. Optically thick emission of the central \( \nu^2 \) (densest/hottest) region
2. Optically thin emission (\( \nu^{-0.1} \))
3. Density gradients along the jet (decreasing the emission)

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.
Young Stellar objects: the role of radio emission

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 suggest the presence of non-thermal emission in some YSO jets.
• 3B. High sensitive radio observations of HH 80-81 confirmed presence of linearly polarized synchrotron emission in HH 80-81.

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

• 5. With high sensitive radio observations, we can study the magnetic field in YSO jets in a similar way as in relativistic jets.

• Disks are often present with sizes 30-300 AU, 0.1 M and 300-1000 AU a few M and clumpy in low/high mass proto stars. Jets have $10^{-5} \sim 10^{-6}$ M yr$^{-1}$ and $v \sim 100$-200 and 200-500 km s$^{-1}$. In high mass stars, disks are confused by the presence of HII region emission
The kinetic energy of the ejected material (outflow/jet) can be transferred to the ambient medium, produce a population inversion of the impacted ambient, and generate maser emission.

Martí et al. 1993: non thermal jet in a high mass object
Young Stellar objects: the role of radio emission

The kinetic energy of the ejected material, as well as radiative energy from the [proto-]star can be transferred to produce a population inversion of the impacted ambient, and *then* generate maser emission

Molecules also emit substantial line radiation
Figure 1.1: Cartoon illustrating the different components within the outflow, together with the temperature stratification. The outflow cavity and the cavity wall are shown, along with the stratification of jet/outflows in low/high mass objects. The disk and the envelope are also depicted, with the UV radiation and the entrained outflowing gas. The different isotopes and molecules, such as \(^{13}\text{CO}\), \(^{12}\text{CO}\), \(^{18}\text{O}\), \(\text{H}_2\text{O}\), are indicated at various temperatures and locations within the outflow region.
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

\[ \text{OH (1965), } H_2O (1969), \text{ CH}_3\text{OH (1970), SiO (1974)} \]

\[ \text{[CH, } H_2\text{CO, NH}_3, \text{ HCN]} \]

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

All have very small linear and angular size (maser spots, often broadened by interstellar scattering)

Transitions of the fine/hyperfine structure of molecules ➔ trace (relatively) cold (& dense) regions of the ISM
Masers

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

\[ \Rightarrow \text{Condensations in the ISM} \]

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)

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!!!
<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:
\[
\frac{dI}{dr} = -\kappa I + \varepsilon \quad \text{where}
\]
\[
\kappa = \frac{h\nu}{4\pi\Delta\nu} (n_1 - n_2)B_{21} \quad \varepsilon = \frac{h\nu}{4\pi\Delta\nu} n_2 A_{21}
\]

At equilibrium, neglecting spontaneous emission and collisions...

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

where \( \Gamma = \text{rate of population redistribution throughout the pump cycle} \) 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. \( \Gamma \gg 2B_{21} I(\Omega/4\pi) \))

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

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

More appropriately:

\[
\frac{dl}{dr} = -\kappa l + \epsilon
\]

where

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

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

At equilibrium, neglecting spontaneous emission and collisions...

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

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.

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\]

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

Standard radiative transfer equation:

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

can be rewritten in terms of temperature

\[
T_B(r) = (T_{B_0} - T_x) e^{-\kappa r} + T_x
\]

where \( T_x \) is the excitation temperature:

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

\( T_x \) 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 $6 \times 10^{-7}$ 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 $2 \times 10^{-7}$ Msun yr$^{-1}$ and 7.5 km s$^{-1}$, respectively.

Each spectrum (right) is a line in the figure on the left (dotted horizontal lines). Times are then smoothed to obtain what we see. Colors represent line intensity.
Interstellar Masers

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

TX Cam: VLBA movie
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 $\text{H}_2\text{O}$) 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$_2$O**: found within parsecs in AGNs (Sy2, Liners, ellipticals)
Strong nuclear water maser at 22 GHz

Megamasers: NGC4258

Single dish Observation

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

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

VLBA: Angular resolution = 200 $\mu$as (0.006 pc at $\sim$ 7.0 Mpc)

Spectral resolution $< 1$ kms$^{-1}$
Megamasers: NGC4258

This Dataset: 18 epochs

1 mas @ 7.2 Mpc $\rightarrow$ 0.04 pc

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

Low-velocity average 1997–2000

Flux Density (Jy)

Radio LSR Velocity (km s⁻¹)

Low-velocity

2.5 Jy
250 mJy
25 mJy
Megamasers: NGC4258

Red-shifted emission

[Graph]
Blue-shifted Emission

Blue-shifted average
1997–2000

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

Flux Density (Jy)

Blue-shifted

2.5 Jy
250 mJy
25 mJy
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%

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

Distance $\sim 7.6 \pm 0.3 \text{ Mpc}$

http://www.ifa.hawaii.edu/users/kud/teaching_15/12_Megamasers.pdf
Megamasers: NGC4258

Black hole mass: $4.0 \pm 0.1 \times 10^7 \, M_{\odot}$

Based on Herrnstein, Greenhill et al. 1998

Arrangement: Greenhill
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