Low-mass (~1 M☉) Star Formation: Disk+Jet system

Magnetocentrifugally accelerated wind

False-color (V, R, I) deconvolved HST WFPC2:
Emission line jet, continuum reflection nebulae,
dark lane.                      (Burrows et al. 1996)

Adapted from
Blandford & Payne 1982
High-mass stars “switch on” still accreting

Impact of radiation pressure and photoionization (thermal pressure from HII regions) on the accretion of circumstellar gas

Do accretion disks exist?

1) photoevaporated by the intense stellar UV Radiation
2) if massive, fragmented by gravitational instabilities
3) destroyed by tidal interactions with (stellar cluster) members

From Observations:
A few B-type YSOs with disks, but no disks towards O-type YSOs
A few thermal jets towards high-mass YSOs (VLA, rms ~ 0.3 mJy)

Are outflows driven by radiation pressure and/or stellar winds?

Does outflow collimation decrease with protostellar mass or age?

Adapted from Beuther & Shepherd 05
Several Molecular Masers commonly observed nearby high-mass YSOs

Maser V_{LSR} + Proper Motions → 3-D kinematics
Are More Massive Stars forming following the same path (disk/jet) as Low-Mass Stars?

Highlights from Maser VLBI towards High-Mass YSOs in order of increasing YSO Mass/Luminosity.
Integrated Intensity epoch-by-epoch (0th Moments)
- Time-series over 2 yrs
- SiO v=1,2
- T=21 months, ΔT~1 month
- R<100 AU, Δθ=0.2 AU

Physical flow of ~1000 independent clumps
- Radial flow (four arms)
- Transverse flow (bridge)

Model
- wide-angle flow (limbs)
- disk rotation

Matthews, Greenhill, Goddi, et al. 2010
3-D velocity field of SiO (v=1,2) maser emission

Disk-Wind Model:
- Edge-on disk
- NE-SW outflow

3-D Velocities:
\[ \Delta v = 5-25 \text{ km/s} \]
\[ V_{\text{ave}} = 14 \text{ km/s} \]

1) Role of magnetic fields from curvature of p.mo trajectories

2) \( M_{\text{dyn, YSO}} \geq 7 M_\odot \) from \( V_{3D} \)

Matthews, Greenhill, Goddi, et al. 2010
Collimated outflow at 100 AU < R < 1000 AU

7mm SiO v=0 J=1-0 (VLA)

Greenhill, Goddi, et al., 2013

Mass-loss \sim 10^{-6} M_\odot yr^{-1}

\begin{tabular}{|l|c|}
\hline
\(<V_{\text{outflow}}>\) & 18 km s^{-1} \\
\hline
\(R_{\text{inn}}\) & 100 AU \\
\hline
\(R_{\text{out}}\) & 1000 AU \\
\hline
\textbf{Mass-loss} & \sim 10^{-6} M_\odot yr^{-1} \\
\hline
\(T_{\text{dyn}}\) & 500 yr \\
\hline
\end{tabular}

Collimated Bipolar Outflow at R~100-1000 AU and V~20 km s^{-1}

• Collimation beyond \sim 100 AU in a straight flow

\textit{Greenhill, Goddi, et al., 2013}
G23.01-0.41

≈ 20 M☉

up to ~20 km/s

P.A.: 58°

1.3 cm radio cont.

= bright knot along the jet axis

12CO (2-1) outflow wings

[48.6,72.8] km s⁻¹

[83.8,108] km s⁻¹

YSO

up to ~60 km/s

Spatial Distribution of Molecular Masers in G23.01-0.41

- H$_2$O 22 GHz
- CH$_3$OH 6.7 GHz
- OH 1.6 GHz

VLA-A

500 AU
Rotation and Expansion @ a few $10^3$ AU from the YSO

What drives the Expansion?

1) A Disk-Wind? (~10 X scaled-up version of that in Source I!)

\[ \text{Dynamical mass } \left( R \cdot V_{\text{rot}}^2 / G \right) \approx 20 \, M_\odot \]

2) A Stellar Wind? (powerful enough from a late O-type star)

\[ L_{\text{bol}} \approx 4 \times 10^4 \, L_\odot \]

\[ M_* \approx 20 \, M_\odot \]

hypercompact HII + dust

O9.5 (20 $M_\odot$) + 130 $M_\odot$
Hypercompact HII region

Moscadelli et al. (2007)
Beltran et al. (2007)

7mm free-free & H$_2$O masers
Hypercompact HII region
Moscadelli et al. (2007)
Beltran et al. (2007)
Water Maser Shell

**Kinematic Status:** \( R_0 \approx 500 \text{ AU} \), \( V_0 \approx 40 \text{ km s}^{-1} \)

Maser Action \( \rightarrow \) pre-shock \( n_H > 10^6 \text{ cm}^{-3} \)

**Wind-driven shell**

For a ZAMS 09.5 type:

\( M_w \approx 10^{-6} \text{ M}_\odot \text{ yr}^{-1}, \ V_w \approx 2000 \text{ km s}^{-1}, \ L_w \approx 1-5 \times 10^{36} \text{ erg s}^{-1} \)

Pressure and momentum-driven solutions require:

\( t_0 \approx 40 \text{ yr}, \ n_H \approx 10^7 \text{ cm}^{-3} \)

Radio appearance similar to an UCHII region
Conclusions and Prospects

Maser VLBI: unique tool to get a “state of art” view of high-mass SF

1) Increasing the sample of MYSOs studied with maser VLBI
Using water and methanol masers to measure trigonometric parallaxes and proper motions of 400 HMSFRs in the MW between 2010 and 2015. Maser Positions and Velocities with accuracy of 1 mas and 1 km s$^{-1}$, suitable for SF study.
Conclusions and Prospects
Maser VLBI: unique tool to get a “state of art” view of high-mass SF

1) Increasing the sample of MYSOs studied with maser VLBI

2) Next, Maser VLBI 3-D velocity fields can be optimally combined with sensitive, $\delta \theta \leq 100$ mas, maps in thermal tracers
Peculiarity of High-Mass (> 6-8 M_{\odot}) Star Formation

![Graph showing time in years against mass (M_{\odot})]
$V_{out} = 18 \pm 8 \text{ km s}^{-1}$

$V_{los}$ gradient $\sim 5 \text{ km/s}$ across minor axis: rotation?

Source I in Orion BN/KL

The most detailed picture of a well-ordered disk/outflow system in a massive YSO

Greenhill, Goddi, et al., 2013
Palla & Stahler (1990)

\[ \frac{dM}{dt} = 10^{-5} \, M_\odot/yr \]
\[ L_{\text{bol}} \sim 10^4 L_\odot \]

\[ 13 M_\odot \]

\[ \text{Hi-GAL} \]
\[ \text{COMICS} \]
\[ \text{De Buizer et al.} \]
\[ \text{GLIMPSE} \]
\[ \text{MIPSGAL} \]
\[ \text{IRAS} \]
\[ \text{MSX} \]
\[ \text{ATLASGAL} \]
\[ \text{BGPS} \]
\[ \text{Beuther et al.} \]

\[ M_{\text{dyn}} = 12 M_\odot \]

\[ \text{CH}_3\text{OH masers} \]
\[ 1.3 \text{ cm continuum} \]

Sanna et al. (2010)

Moscadelli et al. (2013)
Proper motions: CH$_3$OH masers at 6.7 GHz with EVN (3 epochs)

- Dynamical mass ($R \cdot V_{rot}^2/G$)
  - From CH$_3$OH masers: $M_{dyn} \sim 20$ M$_\odot$
  - From CH$_3$CN th.lines: $M_{dyn} \sim 30$ M$_\odot$

CH$_3$OH maser

Expansion: 22 km s$^{-1}$ arcsec$^{-1}$

Keplerian Rotation: 20 M$\odot$