The Most Detailed Picture Yet of a Massive Star in Formation

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How do high-mass stars ($M_* \gg 1 \, M_{\odot}$) form?

— What lies $< 200 \text{ AU}$ from high-mass YSOs?
— Do magnetic fields drive and collimate their outflows?
— Are outflows turbulent?
— Ramifications for pop-III stars?

What is going on in Orion BN/KL?
Why is high-mass star formation poorly understood?

Good examples of accreting massive YSOs are rare.

- Declining IMF
- Distance (> 500 pc)
- Confusion/crowding
- Rapid evolution
- Obscuration
- Poor thermal tracers of gas

Proposed MHD disk winds in high-mass star formation
A Typical Best Case - High-Mass Star Formation via Accretion

Few examples of disks known
- Zhang, Hunter, & Sridharan 1998,
- Shepherd & Kurtz 1999,
- Cesaroni et al. 1999.

None resolved below $10^3$ AU.
- A lot can hide in $10^3$ AU

Limit of imaging thermal gas.
What Drives the Closest Example of High Mass Star Formation?

• Complex outflow structures
• Large variations in reddening
• No center of expansion identified
  – Remnant of explosion? ($\tau \sim 10^3$ yr)
  – Fragmenting stellar wind?

(See also O’Dell et al. 1997, Xu 1996, etc)

Schultz et al. 1999

Orion BN/KL

Allen & Burton 1993

(See also O’Dell et al. 1997, Xu 1996, etc)
Means

- sub-" mid-infrared continuum imaging (Keck)
- cm/mm-wave continuum imaging (VLA)
- cm/mm-wave line imaging (VLBA & VLA)
  - $\text{H}_2\text{O}$ maser
  - $\text{SiO}$ maser ($\nu=0, 1, 2; J=1 \rightarrow 0$)
- moving pictures

Collaborators

Chandler, Danchi, Diamond, Elitzur, Gezari, Menten, Moran, Najita, Reid
A High Density Cluster Core?

Keck LWS mid-IR images of BN/KL

Greenhill et al. 04; see also Shuping et al. 04
What lies < 200 AU from this high-mass YSO?
The 1st direct evidence of an MHD disk wind?

A disk?

Source I (c. 2000.5)

λ7 mm continuum
Menten & Reid in prep.

λ7 mm line
(SiO, v=1, 2)
Greenhill et al.
in prep.
Chandler et al.
in prep.

50 AU
Proper Motion of Molecular Gas
SiO (v=1,2) motion over 4 months

25 AU
Is there a detectable magnetic field?

- Polarization maps trace $\mathbf{B}$ at 200 AU.
- $\mathbf{B}$ is $\parallel$ or $\perp$ to polarization.
- Where would the field come from?
  - Presumably not stellar.
  - Sweeping up of ambient field?
    - Ambipolar diffusion

- Does anisotropic pumping contaminate the polz?
  - Nedoluha & Watson 1994
  - Wiebe & Watson 1998…

Greenhill et al., in prep
Another way to trace magnetic field

- 3-D velocity and accel of gas inside 100 AU.
  - helical flow
  - ballistic flow

- 3-yr VLBA time monitoring will lay out 3-D dynamics.

(Blandford & Payne 82, Pudritz & Norman 86, Ouyed, Pudritz & Stone 97)
Summary I

- Organized accretion/outflow structure in rotation.
- Bipolar, funnel-like geometry
- Indirect evidence for a disk (R>20 AU).
- Time scales are short.
  - Period ~ 30 yr
  - Outflow ~ 20 yr (r = 0→60 AU)
- YSO mass is large.
  - max $|V_{3D}|^2 \sim 2GM/r$  \quad M_* \sim 10 M_\odot
Summary II

- Large inferred mass loss rate.
  - $3 \times 10^{-(4\pm1)} \alpha \, M_{\odot} \, yr^{-1}$ (SiO v=1, 2)
  - $7 \times 10^{-(4\pm1)} \alpha \, M_{\odot} \, yr^{-1}$ (H$_2$O)
  - Low-$\rho$, high-$v$ wind / High-$\rho$, low-$v$ limb?

- Orion BN/KL provides perhaps the only case to directly test whether massive YSO disks drive MHD winds.
  - Test via measurement of $v_{3D}$ and $a_{3D}$ fields.

- And are we any closer to answering the 30 year old question, what powers Orion BN/KL? NO! (cf. Tan/McKee & Tan)
What Drives the Closest Example of High Mass Star Formation?

...probably a cluster

$\text{H}_2$  $\text{Pa} \alpha$  [FeII]

Schultz et al. 1999

...probably a cluster
$20 \text{ km s}^{-1}$ or 
$\sim 0.1''/\text{decade}$

SiO

$v=1,2$
>$10^3 \text{ K}$
$\sim 10^9 \pm 1 \text{ cm}^{-3}$

SiO

$v=0$
$\sim 10^3 \text{ K}$
$\sim 10^6 \pm 1 \text{ cm}^{-3}$

H$_2$O

$6_{16-5_{23}}$
$< 10^3 \text{ K}$
$\sim 10^9 \pm 1 \text{ cm}^{-3}$

R $< 1000 \text{ AU}$

LSR velocity (km s$^{-1}$)
Mass-loaded outflow wall

“Permitted” zones for maser emission

Bipolar outflow
Radial stratification? Rotation?
Masers trace hot, dense gas...

- **H$_2$O**
  - $n_{\text{H}_2} \sim 10^9 - 10^{10} \text{ cm}^{-3}$
  - $T \sim 300 - 800 \text{ K}$
    - *Dusty regions. Collisional pump (shocks).*

- **SiO ($v=1, 2$)**
  - $n_{\text{H}_2} \sim 10^9 - 10^{11} \text{ cm}^{-3}$; $N_{\text{SiO}} \sim 10^{19} - 10^{20} \text{ cm}^{-2}$
  - $T > 1200 \text{ K}$
    - *Dust-free regions. Collisional and radiative pumps.*

- **SiO ($v=0$)**
  - $n_{\text{H}_2} \sim 10^5 - 10^6 \text{ cm}^{-3}$; $N_{\text{SiO}} \sim 10^{16} \text{ cm}^{-2}$
  - $T \sim 800 - 1600 \text{ K}$

- *Close association with young stars.*
- *Quiescent gas.*
A gem is hidden within this "worst case".

Schultz et al. 1999

[FeII]H$_2$ P $\alpha$

HST/Nic

Crowded.

Uncertain Ids of YSOs. Multiple outflows.

Patchy obscuration, $A_V$ of a few to 500.

Gezari et al. in prep.

Danchi et al. in prep.

Greenhill et al. in "
What powers Orion BN/KL?

- Probably not source I *alone*
  - The h.v. flow is shadowed.
  - Src I flows are “compact.”
  - There are many YSOs in the vicinity.
- However
  - Alignment with the 18 km/s flow is good, and
  - Mass loss may be episodic
What is Source I?

(c. 1997)

H$_2$O

SiO (v=1)

~100 AU

See also

Greenhill et al. (1998)
Doeleman et al. (1999)
Plambeck et al. 1990
Morita et al. 1992
Menten & Reid 1995
Genzel & Stutzki 1989
More Questions…

- Is the model antropocentric?

- Is Source I unique?
  - Yes, in terms of proximity.
  - But, possibly similar source in W51 IRS2 (Eisner et al.).
  - No reported southern sky surveys for interstellar SiO masers.

- An especially short evolutionary phase for massive YSOs?

- Maser emission can be a highly specific tracer.

Is there danger here?

P.O.V. in outer galaxy
Are Magnetic Fields Important?

- Evaluate 3-D gas dynamics
  - $v=1,2$ SiO masers @ $R<10^2$ AU
  - Radiation-driven disk winds?
  - Hydromagnetic disk winds?
    - Blandford & Payne 82, Pudritz & Norman 86,
      Ouyed, Pudritz & Stone 97
  - Where would the field come from?
    - Presumably not stellar.
    - Sweeping up of ambient field?
      - Ambipolar diffusion

- Measure linear polarization
  - $v=0,1,2$ SiO masers @ $R<10^3$ AU
Key Science Questions

- What does HMSF look like?
  - Structure @ R= 20-10^3 AU
  - 3-D gas dynamics @ R= 20-10^3 AU

- Are magnetic fields important?
- Is source I important (to BN/KL)?
- Are outflows turbulent?
- Can more massive stars form in the same way?