SiO Outflows as Tracers of Massive Star Formation in Infrared Dark Clouds

Mengyao Liu, Jonathan C. Tan, Shuo Kong

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Massive Star Formation

- “Standard” model of isolated low-mass star formation

- Massive Star Formation??
  - Difficulty in observation
  - Turbulent Core Accretion vs. Competitive Accretion vs. Protostellar Collision

(Shu+ 1987)
Evolutionary Sequence for Massive Star Formation

- **Cold Collapsing Core**
- **Hot Molecular Core**
- **Hyper Compact HII Region**
- **Ultra Compact HII Region**
- **HII region / OB Association**

(Credit: Cormac Purcell)
Outline

- Pre-stellar Cores —— $\text{N}_2\text{D}^+$
- Early-stage Protostars —— SiO
  - SiO detection
  - SiO and 1.3mm continuum
  - SiO and infrared emission
- Later-stage Protostars —— MIR, FIR
A Hunt for Massive Starless Cores

- 30 clumps in 7 *Infrared Dark Clouds (IRDCs)* (2.4-5.7 kpc)
- Over 100 $N_2D^+$ cores identified as *pre-stellar* candidates (Kong+ 2017)
- SiO outflows as a tracer of *protostars* (Liu+ in prep.)

**IRDC-C Spitzer 8µm**

**ALMA Cycle 2**

- Band 6: 1.3mm continuum, $N_2D^+(3-2)$, $C^{18}O(2-1)$, SiO(5-4), DCN(3-2), DCO+(3-2), CH$_3$OH(5-4).
- Angular resolution ~1”. Sensitivity: 0.2mJy/beam for continuum, 20mJy/beam/0.2km/s for molecular lines.
SiO(5-4) over 1.3mm continuum

PV Diagram
C9

SiO(5-4) over 1.3mm continuum
SiO Detection

- Detected SiO emission in 20 out of the 30 clumps.
- Detection rate: 67%
  - 95% López-Sepulcre et al. 2011 for IR-dark clumps
  - 61% Csengeri et al. 2016 for IR-quiet clumps
- 17 clumps: SiO & continuum & dense gas
- 6 clumps: SiO stronger than 10σ & continuum & dense gas
SiO and Continuum Cores

- 17 clumps: SiO & 1.3mm continuum & dense gas
- 4 high-mass cores (7-370M☉):
  - A1, C2, C9, D9
- 6 intermediate-mass cores (2-15M☉):
  - A3, B2, C4, C6, D6, H5
- But we miss flux...

T for cores: 20 - 50 K
SiO Outflow Properties

- Mid- to early-B type stars
  - Mass outflow rates $\sim 10^{-5}$ to a few $\times 10^{-3} \, M_\odot/\text{yr}$
  - Momentum rates $\sim 10^{-4}$ to $10^{-2} \, M_\odot \, \text{km/s}/\text{yr}$

(Arce et al. 2007)

- LTE, optically thin
- $T$ for outflows: 18K
- SiO abundance: $H_2$/SiO$\sim 10^9$

### Table 3. Estimated physical parameters for SiO outflows

<table>
<thead>
<tr>
<th>Source</th>
<th>$M_{\text{out}}^{\text{blue}}$ ($M_\odot$)</th>
<th>$L_{\text{flow}}^{\text{blue}}$ (pc)</th>
<th>$t_{\text{dyn}}^{\text{blue}}$ ($10^3$ yr)</th>
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<th>$M_{\text{out}}$ ($M_\odot$)</th>
<th>$P_{\text{out}}$ ($M_\odot , \text{km s}^{-1}$)</th>
<th>$E_{\text{out}}$ ($10^{43}$ erg)</th>
<th>$\dot{M}<em>{\text{out}}$ ($10^{-4} , M</em>\odot , \text{yr}^{-1}$)</th>
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<tbody>
<tr>
<td>B1</td>
<td>0.004</td>
<td>0.03</td>
<td>5.23</td>
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Early-stage or SiO not tracing the full extent

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Infrared Emission

70μm Herschel image
SiO
1.3mm continuum
Infrared Emission

8μm  24μm  70μm  160μm

C6  C6  C6  C6

C9  C9  C9  C9
Infrared Emission

- Aperture photometry
- SED fitting
  - Zhang & Tan Radiative Transfer (RT) Models
  - Based on Turbulent Core Accretion Scenario
  - Five free parameters: $M_c$, $\Sigma_{cl}$, $m_*$, $\theta_{view}$ and $A_V$
Infrared Emission

- Aperture photometry
- SED fitting

- Luminosity $\sim 10^1$-$10^3$ L$\odot$, C9 $< 5\times10^3$ L$\odot$
- Returned protostellar mass $\sim 0.5$-$4$M$\odot$

- Lack of MIR emission
- Low luminosity
- Low current stellar mass

> Early Stage
$L_{\text{SiO}}$ vs. $L_{\text{bol}}$

- $L_{\text{SiO}}$ tend to be proportional to $L_{\text{bol}}$ in a large $L_{\text{bol}}$ span

- More powerful shocks?

SiO (5-4) data in this paper
SiO (2-1) data from Duarte-Cabral et al. (2014)
SiO (5-4) data from Csengeri et al. (2016)

$f(x) = 0.63x + 7.44$

$\alpha = 0.63 \pm 0.08$
Later-stage Protostars

- SOFIA MAssive (SOMA) Star Formation Survey
- 10 to 40μm images
- 22 protostars observed by the end of Cycle 4
- 30" scale bars
- 37μm images
High resolution MIR and FIR images which reveal heated outflow cavities.

Extended MIR emission that aligns with known outflows

Brighter on the near-facing, blue-shifted side, more symmetric at longer wavelengths

SEDs can be well fit by Zhang & Tan RT models and yield key physical parameters

SED fitting with Zhang & Tan RT models

(De Buizer+ 2017)
Future Work

onset of ionization in early-stage protostars

ALMA

hyper-compact sources

VLA

more evolved sources

SOFIA

hyper-compact sources

Cold Collapsing Core

Hot Molecular Core

Hyper Compact HII Region

Ultra Compact HII Region

HII region / OB Association

Clumpy Molecular Cloud

Cold Collapsing Core

Hot Molecular Core

Ionized gas

Chemical Shells

SiO

CH$_3$CN

HCO$^+$

HCN

Clumpy Molecular Cloud

5x10$^4$ Years

1x10$^5$ Years

1.5x10$^5$ Years

(Credit: Cormac Purcell)
Take-away

- Characterize sources from pre-stellar phase to hyper-compact phase in different high-mass star forming regions with different tracers.
- SiO outflows seem to be a valid tracer of massive protostars in IRDCs.
Thanks!