3-D Shock Physics of Outflows with IGRINS

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Outflows with IGRINS

@2.7m HJST/McD
@4.3m DCT/Lowell
@ 8.1m Gemini-S 2018A

- Highly sensitive, Large $\lambda$ coverage in NIR 1.49 – 2.46$\mu$m
- High resolving power $\sim$ 45,000 (7 km s$^{-1}$)

✓ Powerful tool to study complex inner structures of dense molecular cloud
✓ Datacube by spectral mapping $\Rightarrow$ 4-D laboratory; x, y, velocity & lines


\[
\text{H}_2, \, [\text{Fe II}] \text{ lines - Shock tracer Br series}
\]
Contents

1. High velocity H\textsubscript{2} in bow shock \textit{with Gemini S}

2. 3-D Shock structure of Orion BN/KL using spectral mapping
High Velocity H$_2$ in Bow Shock

Bow-shock with extremely high-velocity H$_2$ Emission ($V_{\text{Radial}} \sim 50-200$ km s$^{-1}$), far beyond the dissociative shock velocity (e.g., L1551 IRS5, HH7)

IGRINS+Gemini South

- High resolution spectroscopy with **spatially resolved** bow-shock
- Low- and high-velocity H$_2$ emission:
  - Deep exposure (>3 hr) will obtain weaker, high excitation lines ($v \geq 3$) from high-velocity component

MHO 1915 in IRAS 17233-3606

- Bow-shaped emission associated with massive star forming region IRAS 17233-3606
- Masers e.g., OH & H$_2$O (Caswell & Haynes 1980, 1983), Multiple outflows including extremely high-v CO (>150 km s$^{-1}$)

*MHO: Catalogue of Molecular Hydrogen Emission-Line Objects in Outflows from Young Stars*
High Velocity H$_2$ in Bow Shock

Position velocity map of H$_2$ 1-0 S(1)

- Few $v \geq 3$ lines (obtained $\sim$50% of expected S/N due to weather constraint)
- $T_{\text{ex}}$ is 300-2500K higher in high-velocity over $v=1$-3
- Evidence of H$_2$ reformation? (e.g. Pike et al. 2016)

More is coming!
Orion KL

Subaru, Kaifu+ (2000)

Orion KL

θ¹ Ori c

Orion bar PDR

HST/visible, ~0.5°
Orion KL Outflow

- BN/KL region in OMC-1 at 414 pc (Menten+ 2007)
- Explosive massive outflow with kinetic energy >4 x 10^{46} erg (Snell+ 1984)
- Outflow origin is Not clear
  - Dynamical decay of multiple-system (Bally & Zinnecker 2005)
  - Ejection of BN object from trapezium 4000 yr ago and its passage of OMC1 core 500 yr ago? (Tan 2004)
- Other explosive flows in massive star forming region in our galaxy: DR 21 (H2), W 49 and W 51 (H2O masers)
- We study shock & bullet structure in 3-dimension
  - Orion KL is nearby
  - imaging + spectroscopy allows to resolve and study high velocity shocks in the dense ISM
Observation: Spectral Mapping

1”x15” slit

Chain of bows
HH 205-207:
12” x 54”
52 positions,
450 sec

Data Reduction

- IGRINS Pipeline (Lee+ 2016)
- Normal spectral reduction
- Plotspec (Kaplan+ 2017)
- Building a dataCube
- Spatial registration, combining,
  relative flux calibration,
  continuum subtraction

Image: [Fe II] and H₂
(Bally+ 2015)
Previous Study

H2 1-0 S(1)
UKIRT WFCAM

H2 1-0 S(1)
IGRINS DataCube Movie

\[ V_{\text{LSR}} = -135 \text{ km s}^{-1} \]

+ : star positions (subtracted)

\[ V_{\text{sys}} = +8 \text{ km s}^{-1} \]

Oh et al. (2016)

Three-dimensional Structure of Fingers

Internal Extinction

- \( N_H \sim 1.6 \times 10^{22} \text{ cm}^{-2} \)
- \( n_H \sim 10^5 \text{ cm}^{-3} \)
**Observation: Spectral Mapping**

**Chain of bows**

HH 205-207: 12″×54″
52 positions, 450 sec

**GSAOI H₂**

**BN**

**Oh+ 2016:**

H₂ Peak1, 15″×13″

**Follow up study toward HH 205 - 207**

- Peak 1 region is complex: close to the shock origin, many bow-shocks spatially overlapped.
- HH 205 - 207
  - Farther from the ejection center
  - Clearer view of the shock physics of a single isolated bullet

- Spatial registration, combining, relative flux calibration, continuum subtraction

**Image:** [Fe II] and H₂ (Bally+ 2015)
**Image & Channel Map**

- Simpler velocity profile than peak 1 region. Major stream is in \(-30 < V_{\text{LSR}} <+30 \text{ km s}^{-1}\): bow axes are closer to plane of the sky with high \(V_{\text{proper}}\) 100-300 km s\(^{-1}\).
- \([\text{Fe II}]\): dominant in farther bullets (e.g., Bally+ 2015), \(\text{H}_2\): High velocity knots only seen in bullets behind: shock is faster (dissociative) in bullets ahead and slow down.
- \(V_{\text{MAX}}\) and \(\text{FWHM}\) are larger in \([\text{Fe II}]\) than \(\text{H}_2\) (\(V_{\text{MAX}} \sim 150\) and 90 km s\(^{-1}\) & \(\text{FWHM} \sim 85\) and 30 km s\(^{-1}\)).
Velocity Structure

Mean velocity field

H₂:
- \( V_{\text{Mean}} \pm 10 \text{ km s}^{-1} \) around \( V_{\text{sys}} \)
- Similar fraction of blue and redshifted components
- Blue & red components trace bow axis
  - Expanding bow? - not likely
  - Rotating bows? - no, blue & red trace flow axis than side wing
  - Different flows - overlapped flows

[Fe II]:
- \( V_{\text{Mean}} \pm 30 \text{ km s}^{-1} \) around \( V_{\text{sys}} \)
- Mostly blueshifted (extinction?)
- again tracing flow axis
H$_2$ Line Ratio

V$_{total}$

Channel map

2-1/1-0 S(1)

Other high excitation lines?
1-0S(1) 2-1S(1) 3-2S(3) 6-4S(1) 7-5S(3)

Excitation Diagram

- UV excited ambient + shocked outflow
- $T_{EX}$ is higher toward NE
  - Geometrical effect by clumpy foreground?
  - or UV irradiated jet?

• Mostly UV
• UV + shock
• Mostly shock

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Summary

- Outflows with IGRINS
  - Wide wavelength coverage, high-resolving power, high-sensitivity
  - 4-D (x, y, v, lines) datacube in dense molecular clouds by spectral mapping

- Bow-shock with high-velocity H$_2$ Emission
  - 300-2500 K higher $T_{ex}$ in high-velocity component

- Datacubes from Orion KL
  - Peak 1: 3D finger map, internal extinction in dense molecular cloud with complex geometry
  - Chain of bows HH 205 - 207: Simpler PV profile, bow axes are close to plane of the sky, UV + Shock excited outflow

- Future work:
  - Analyse PV profiles with bow shock models
  - More line ratios: H$_2$, Br series, [Fe II] $\Rightarrow T_{EX}$, Av, N$_E$
  - Connect observed dynamics and physics to the whole Orion KL system
Thanks!

IGRINS emits Rainbow in Dark