Molecular Line View in the Heart of Orion Nebula

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• Review of topics presented in the WS
• Examples of case studies for high-mass star-forming region (SFR)

1. Distance measurement
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My current research interest

- Physics and chemistry in high-mass star-formation processes
  - Significant impact on evolution of galaxies and universe
- Still challenging for high resolution/sensitivity studies
  - Smaller population and shorter lifetime; rare objects
  - Usually farther distance except a few nearby targets
  - Formed in dense cluster; need high resolution
My favorite target

• Orion KL nebula in M42 (Kleinmann & Low 1967)
  – The nearest site of high-mass star-formation; high sensitivity/resolution
  – One of the first targets for new telescopes to receive the first light
  – Various intriguing phenomena related to star-formation processes
1. Distance measurement
H$_2$O masers in Orion KL

- One of the first targets for VERA
  - Famous for strong H$_2$O maser at 22 GHz
  - Best target for astrometry observations
  - Recall lectures by Rioja and Honma

Subaru NIR image (Kaifu+2000)

H$_2$O maser map and spectra with VERA (Hirota+2007)
Astrometry with VERA

- One of the first results from VERA astrometry
  - $2.29 \pm 0.10$ mas = $437 \pm 19$ pc (Hirota+2007)
  - Revised later; $414 \pm 7$ pc (Menten+2007) and $418 \pm 7$ pc (Kim+2008)
  - 20% smaller values than widely accepted value of 480 pc (Genzel+1981)

Subaru NIR image (Kaifu+2000)

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2. Outflow and disk
Complex outflows in Orion KL

- From large scale to small scale structure of outflow and jet
  - High velocity explosive outflow (IR; Kaifu+2000, Radio; Bally+2017, etc.)
  - Low-velocity outflow (H$_2$O maser; Hirota+2007, SiO thermal lines; Niederhofer+2012, etc.)
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  - Very rare SFR with SiO masers (Kim+2008, etc.)
Unresolved issues

• Basic properties of outflow and jet in Orion KL?
  – What is the nature of the powering source?
  – What is the origin of outflows?
  – How are high-mass stars in Orion KL forming and evolving?

• Need high resolution radio observations
  – Resolve the structure deeply embedded and obscured in the host cloud
Our probes for ALMA

• Submillimeter H$_2$O lines and SiO lines
  – Various lines at different energy levels
  – High resolution with masers
  – Complementary with 22 GHz H$_2$O and 43 GHz SiO maser data with VLBI
Powering source in Orion KL

- Detection of high excitation submillimeter H$_2$O lines ($E_t=3500$ K)
  - Coincident with the center of SiO masers and a radio continuum emission "Source I" (Menten & Reid 1995)
  - Different structures in different lines
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HCOOCH$_3$ line map with ALMA (Hirota+2014)
Spatial and velocity structures

- Different structures but similar velocity gradients in all lines
  - Compact structure (e.g. H$_2$O line at 463 GHz, 336 GHz)
  - Extended structure (e.g. H$_2$O line at 321 GHz, Si$^{18}$O line at 484 GHz)
  - Common for all lines including SiO masers (VERA; Kim+2008)

- How to interpret?

Moment 1 maps for Si$^{18}$O at 484 GHz and H$_2$O at 463 GHz (Hirota+2017)
PV diagrams

- Velocity structure perpendicular to outflow
  - Rotating ring close to center
  - Rotation and radial expansion away from the center
  - Consistent with rotation with $M = 8.7 +/- 0.6 \, M_{\text{Sun}}$

Moment 0 map for $\text{Si}^{18}\text{O}$ at 484 GHz and PV diagrams (Hirota+2017)
Rotation of outflow

• Possible solution for “angular momentum problem”
  – One of the long-standing issues in star-formation processes
  – Same as low-mass cases
  – Recall lecture by K. T. Kim

\[ \Omega(r) = \left( \frac{R}{r} \right)^2 \Omega_0 \]
Alternative scenario?

• 5-7 (or 8)\(M_{\text{Sun}}\) protostar with accretion disk
  – PV map of molecular lines (e.g. Kim+2008, Hirota+2014, 2017)

• 20\(M_{\text{Sun}}\) binary formed by dynamical decay around 500 yrs ago
  – Proper motion (e.g. Rodrigues+2017)
  – Explosive outflow (e.g. Bally+2017)
3. Supermaser

Spectra of Orion supermaser (Hirota+2011, 2014)
Variability of supermaser

- “Burst” of 22 GHz H$_2$O “supermaser”
  - 1979-85 (Garay+1989 etc)
  - 1998-99 (Omodaka+1999 etc.)
  - 2011-2012 (Hirota+2011, 2014)
  - 13 yr period? (Tolmachev 2011)
  - Recall lecture by Kramer
Possible origin of supermaser

- Properties of supermaser observed with VERA and ALMA
  - Located in shocked region; Compact Ridge
  - Proper motion parallel to outflow
  - Related to mass ejection/accretion process?
    - Recall lectures by Sugiyama and Kramer

Proper motions of Orion supermasers observed with VERA (Hirota+2011, 2014)

Supermaser position superposed on molecular line map (Hirota+2014)
4. Chemistry

ALMA SV data for Orion KL
Mapping data with ALMA

- Know as prototype “Hot (Molecular) Core”
  - Rich chemistry showing line forest (or weed)

Dust continuum map with ALMA (Hirota+2015)
Chemical differentiation

- Depending on physical properties previously proposed (Sutton+1995, Beuther+2005)
  - N-bearing species in Hot Core at higher temperature
  - C-bearing species in Compact Ridge
  - Effect of star-formation (e.g. explosive or bipolar outflow?)
  - Still not fully understood, still many unidentified transitions

Molecular line map with ALMA (Yamamoto+2017, Hirota unpublished)
Summary

• Orion KL is one of the nearest and most studied high-mass star-forming regions at the highest resolution, but still enigmatic
  – What is the mass of Source I?
  – How is the Source I system forming and evolving?
  – What is the origin of proper motions in Orion KL?
  – How is the chemical processes in Orion KL?
  – What is the origin of the supermaser activities?
  – Is Orion KL a very peculiar source or typical high-mass SFR?

• Please consider future TNRT projects for one the above topics
  – We still need more detailed observations in Orion KL
  – We also need more data for other sources for comparison
  – We will welcome new collaborators!