Recent progress in high-mass star-formation studies

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My talk

• Review broad context of high-mass star-formation studies
  – Mainly focus on recent progress of observational studies
  – Not well focus on cosmic cycle of dust and gas

• Contents
  – Introduction
  – Representative recent results, especially from ALMA
  – A few examples of our studies
What is HM star? Why important?

• How high mass (HM)?
  – Early B (B3 and earlier) and O stars
  – More massive than $8M_{\text{Sun}}$
  – More luminous than $10^3 L_{\text{Sun}}$

• Significant impacts on astronomy, astrophysics, and astrochemistry
  – Influences on surroundings by strong UV, wind, explosion, ...
Scale of high-mass Star-forming regions

- From giant molecular cloud (GMC) complex to high-mass (HM) young stellar object (YSO)
  - Large-scale structures affected by YSO-scale events

In case of Orion (Hirota+2018)
Why so difficult?

- Intrinsic characteristics of HM-YSOs/SFRs
  - 100 times rarer probability than low-mass stars
  - 1000 times shorter lifetime than low-mass stars
  - >10 times larger distances than low-mass SFRs
Why so difficult?

- Observationally still challenging
  - Usually formed in clusters
  - Extremely high opacities unreachable at IR or shorter wavelengths
  - Only achievable by interferometers to resolve innermost structures
Fundamental questions

• How can HM-protostellar objects accrete their mass within short lifetime against strong feedback?

• What is initial condition for HM star-formation?

• How is stellar initial mass function determined?

• How to solve these problems?
  – Study dynamical properties from host clouds to HM-YSOs
  – Chemistry complementary to physical/dynamical properties
  – Theoretical works also essential to interpret observational results
Accretion at clump and core scale

- Two controversial theories

- Turbulent core accretion (e.g. McKee & Tan 2002)
  - Scale-up of low-mass case (monolithic collapse)
  - High mass single YSO (binary or small cluster) formed in a single massive turbulent core
  - Forming disk/outflow system

- Competitive accretion (e.g. Bonnel+1997)
  - High mass YSO formed in the center of low-mass cores/YSOs via global collapse
  - Fragmentation into small cores with thermal Jeans mass
  - More disturbed disk/outflow system
Infrared dark clouds (IRDCs)

- Good laboratory for investigating initial conditions
  - Characteristic filamentary structures sometimes with global inflow
  - e.g. SDC335; most massive core in the Galaxy (545 $M_{\odot}$ at MM1) at infalling rate of $2.5\times10^{-3} M_{\odot} \text{yr}^{-1}$; Peretto+2013, Avison+2015

Spitzer image, intensity, and velocity maps of $N_2H^+ (1-0)$ line in SDC335.579-0.272 at 3.25 kpc (Peretto+2013, Avison+2015)
Infrared dark clouds (IRDCs)

• Search for massive starless (prestellar) cores/clumps
  – e.g. G011.92-0.61 MM2; massive (>30 $M_{\odot}$) core without any sign of star-formation activity (Cyganowski+2014, 2017)
  – e.g. G028.37+00.07; chemically evolved, massive (~60 $M_{\odot}$), magnetically virialized starless cores (Tan+2013, 2016, Gong+2016)
  – Still rare cases (and still not convincing)

CO (3-2), 1.3mm continuum, and Spitzer maps of G11.92-0.61 at 3.37 kpc (Cyganowski+2014)

N2D+ (3-2) maps superposed on MIR extinction image of Spitzer and CO (2-1) outflow map of IRDC G028.37+ 00.07 at 5 kpc (Tan+2013, 2016, Kong+2016)
Accretion at YSO scale

- Well known feedback problem
  - Accretion suppressed by strong radiation pressure
  - Higher accretion rate than low-mass YSOs
  - Solved by non-isotropic accretion through disk ("flashlight effect"; Yorke & Bodenheimer 1999)

Possible stellar mass as functions of mass accretion rate (Wolfire & Cassinelli 1987)

IR image of IRAS20126+4104, suggesting outflow cavity and edge-on disk (Cesaroni+2013)
Circumstellar disks before ALMA

- Discovered by various tools, but mostly in B-type YSOs

**Millimeter line (PdBI)**
- Molecular line maps of IRAS 20126+4104 by PdBI (Cesaroni+2006)

**NIR continuum (VLTI)**
- Model and VLTI image of IRAS 13481-6124 (Kraus+2010)

**Masers (VLBI)**
- SiO maser map of Orion Source I by VERA (Kim+2008)

**Radio continuum (VLA)**
- H$_2$O (left) and CH$_3$OH (right) masers and VLA continuum map in G353.273+0.641 (Motogi+2017)

**CH$_3$OH maser map of Cepheus A by JVN(Sugiyama+2014)**
Circumstellar disks seen by ALMA

- Even for distant O-stars
  - Keplerian rotation, infall
  - Accretion rate $\sim 10^{-3} M_{\text{Sun}} \text{ yr}^{-1}$
  - More complicated due to outflow, fragment, binary?

Keplerian disk around AFGL4176 at 4.2 kpc (Johnston+2015)

Outflow and disk in G29.96 at 5.26 kpc (Cesaroni+2017)

Map and spectra of G351.77-0.54 at 2.2/1 kpc (Beuther+2017)
Case study of disk/outflow in Orion

- Radio source I in Orion KL
  - One of the well studied high-mass YSO
  - ALMA observations of high-energy lines at 0.1” resolution (~42 au at 420 pc distance; (Hirota+2007, Menten+2007, Kim+2008)
  - Velocity gradient perpendicular to outflow

Outflow rotation in Orion Source I (Hirota+2017)
Detailed structure of outflow

- Rotating and expanding structure
  - Enclosed mass of $8.7_{-0.6}^{+0.6}$ $M_{\text{Sun}}$
  - Centrifugal radii of $21-47$ au
  - Velocity of $\sim 10$ km s$^{-1}$ (no high velocity jet)
  - Rotating and radially expanding outflow

PV diagram in Orion Source I (Hirota+2017)
Evidence of rotating outflow/jet

- Consistent with magneto-centrifugal disk wind model
  - Possible Solution for angular momentum problem
  - Same as low-mass YSOs
  - Still challenging, need more data (see review by Belloche+2013)
More recent studies

- High excited lines of H$_2$O, SiO, and their isotopologues
  – Recall Wong’s talk (AGB)

- Keplerian rotation around 15+/-2 M$_{\text{sun}}$ YSO(s)

Moment 0 maps of U230.322 and 232 GHz H$_2$O (v=1) lines (Ginsburg+2018)

Moment 0/1 maps SiO v=1 and v=4, J=11-10 line (Hirota+2018)
Complex structure of outflows

- Bipolar and explosive outflows in Orion KL
  - Energy release of $10^{48}$ erg via dynamical decay of multiple system (e.g. Rodriguez+2017, Orozco-Aguilera+2017, Bally+2017)
  - Formation of a binary with $\sim 20M_{\text{Sun}}$ (Ginsburg+2018)
Accretion burst in HM-YSOs

- Luminosity in S255 NIRS3 from $2.9 \times 10^4 L_{\text{Sun}}$ to $1.6 \times 10^5 L_{\text{Sun}}$
  - First detected by methanol maser flare by single-dish monitoring (Fujisawa+2016, Moscadelli+2017)
  - Subsequent follow-up observations in continuum from IR to radio (Caratti o Garatti+2016, Cesaroni et al. 2018)
  - Suggesting accretion burst with mass accretion rate of $5 \times 10^{-3} M_{\text{Sun}}$
Accretion burst in HM-YSOs

- Luminosity increase by 70 \((4.2 \times 10^4 \text{L}_{\odot})\) in NGC6334I MM1
  - Both continuum and masers (Hunter+2017, MacLeod+2018)
  - Masers can be unique probes for episodic accretion burst

Millimeter and maser outburst in NGC6334I MM1 (Hunter+2017, 2018, MacLeod+2018)
Summary and future prospects

• Observational studies at high resolution/sensitivity reveal
  – Global structure of IRDC clumps/cores
  – Potential but not convincing candidates of massive prestellar cores
  – Disks around O- and B-type YSOs with possibly Keplerian rotation
  – Outflow rotation in Orion Source I similar to low-mass YSOs
  – Episodic accretion burst events also identified by maser variability

• Not discussed in my talk but here emphasize importance of
  – Theoretical works to cover large dynamic range of HM-SFRs
  – Further systematic survey at higher resolution/sensitivity
  – In particular chemistry and polarization (magnetic field)