Physical properties and evolution of GMCs in the Galaxy and the Magellanic Clouds

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GMC as a site of high-mass star formation

From galaxy evolution to individual star formation

- kpc
- 1-100pc
- <0.1 pc

GMCs: $10^4 - 10^6$ Mo
$n(H_2) \sim 1000$ cm$^{-3}$

Clumps, Cores
$10^2 - 10^3$ Mo
$n(H_2) \sim >10^4$ cm$^{-3}$

Wide range of scales
Various distances
Use of various telescopes

GMAs: $10^7$ Mo
Star formation in GMCs

★ Most stars form in GMCs
  ✷ K-S law: Gas surface density – SF activities
    - Gas → SF is a “key” to understand the galaxy’s evolution

★ Key issue for galaxy evolution
  ✷ GMC properties in the MW as templates
    - Some scaling relations (e.g., Solomon et al. 1987)
    - The samples are biased to the nearby GMC?
      ✷ Not a representative for the MW?
  ✷ Magellanic Clouds + some local galaxies
    - Recent high resolution observations + “Uniform” sample
      ✷ Uniform sample of high mass formation from GMC scale down to core scale
    - bridging between MW GMCs and distant galaxies
High mass SF

★ Initial condition
  ✷ Need high Jeans mass (effective $a \approx 10$ km/s)
    - Monolithic collapse? (McKee and Tan 2002)
    - Competitive mass accretion? (Bonnel et al. 2010)
  ✷ Origin of IMF
  ✷ Effect of the total mass of the cloud?
  ✷ Origin of isolated high mass star: 20%? (Gies 1987)

★ Rapid destructive process
  ✷ Information on natal clouds dissipates very fast.
Progress

★ High precision (large aperture) telescopes with sensitive receivers installed
  ✧ NANTEN2 4m
  ✧ NRO 45m, IRAM 30m
  ✧ ASTE 10m, APEX 12m

★ Sensitive receivers at higher freq. and telescopes at high site
  ✧ CO (J=2-1,3-2,4-3,6-5,7-6,…)

★ ALMA
  ✧ Spatial scale: 0.01 ~ 100 arcsec
  ✧ Band 6 and Band 7 observations of external galaxies
    - Highly efficient
Galactic plane surveys

- Sites of high-mass star formation in the Galaxy.
- CO, $^{13}$CO, C$^{18}$O, J=1-0: Mass tracers
- J=2-1, 3-2 lines: Density, temperature dependent

- Angular resolution: 3 arcmin
  - NANTEN2 4m: $^{12}$CO(1-0), $^{13}$CO(1-0), Entire Southern Sky
  - Osaka 1.85m at NRO: $^{12}$CO(2-1), $^{13}$CO(2-1), C$^{18}$O(2-1), Northern sky
  - Angular resolution: better than ~1’
    - FCRAO 14m: $^{13}$CO(1-0), 55.7°>L>18°, |b|<1°
    - Mopra 22m: $^{12}$CO(1-0), $^{13}$CO(1-0), C$^{18}$O(1-0), 358°>L>300°, |b|<0.5°
    - JCMT 15m: $^{12}$CO(3-2), $^{13}$CO(3-2), C$^{18}$O(3-2), 43°>L>28°, |b|<0.5°
    - NRO 45m: $^{12}$CO(1-0), $^{13}$CO(1-0), C$^{18}$O(1-0), 50°>L>10°, 236°>L>198°, |b|<1°
CO three lines

~JCMT CO(3-2) resolutions

R $^{12}$CO(1-0), G $^{13}$CO(1-0), B $^{18}$O(1-0)
Why filamentary clouds?

To understand roles of filaments in SF are quite important!

(e.g., Inutsuka & Miyama 1997, Arzoumanian et al. 2010, André et al. 2014)

Spatially resolved observations (<0.1 pc) of filaments in (galactic) massive star-forming regions are very rare so far...

Possible formation mechanisms of massive filaments:
- Recent large-scale compression
- Dynamically supported by accretion driven MHD waves

(André et al. 2016)
Sites of the massive star formation by CCC

- PASJ Special Issue : CCC (May 2018)
- Single O star formation
  - Spitzer bubbles (RCW79, N35, etc.)
  - UCHII region (RCW166 : Ohama+18b)
- Galactic mini-starbursts
  - NGC6334+NGC6357 (Fukui+18b)
- High-mass star cluster formation
  - M17 (Nishimura+18), W33 (Kohno+18)
  - Vela region (Sano+18, Hayashi+18, Enokiya+18)
ALMA
Magellanic Clouds

- D~ 50 kpc (one of the nearest)
- Different environment from the MW.
  - High gas-dust ratio
  - Low metallicity
- Active star formation
  - Massive star formation
  - Young populous clusters

The Large Magellanic Cloud

The Small Magellanic Cloud
N159: One of the largest GMCs in the LMC
10$^7$Mo, 220pc, Four young clusters (age <10Myr)
ALMA observations: Cycles 1 and 4
NANTEN (40 pc), Fukui et al. 2008

Strongest CO(3-2) in LMC

ASTE (5 pc), Minamidani et al. 2008

Saigo et al. 2017

- beam(~0.3 pc)

Fukui et al. 2015

- beam(~0.3 pc)
N159W

13CO(2-1)

Massive Protostar

Massive Protostar

Integrated Intensity (Jy/beam km/s)

RA (J2000)

Dec (J2000)

5pc
Massive star formation by cloud-cloud collisions

3-D MHD simulation with self-gravity of colliding clouds
Inoue & Fukui 2013

Large effective Jeans mass owing to the enhancement of the magnetic field strength by shock compression and turbulence in the compressed layer
Papillon nebula
(Compact HII region: 50Mo star?)
$^{12}$CO $(J = 2-1)$

Osaka
1.85-m

Beam: 0.35 pc

Nishimura et al. (2015)

ALMA Cycle1

Beam: 0.24 pc
$^{13}\text{CO}$

$\left( J = 2-1 \right)$

Nishimura et al. (2015)
Moment 0 map ($^{12}$CO ($J = 2−1$))

Integrated intensity (K km/s)

0 100 200 300 400

Orion-B  Orion-A  N159W-S  N159E-Papillion  N159W-N

Osaka 1.85-m  ALMA Cycle1
Moment 0 map ($^{13}$CO ($J = 2-1$))
Channel map ($^{12}$CO ($J = 2−1$))
Moment 1 map ($^{12}$CO ($J = 2-1$))

Complex velocity field

=> Components having different velocities
$^{13}\text{CO}$ ($J = 2-1$)

Osaka 1.85-m (~3’)

W43 (Carlhoff+2013)

IRAM 30-m (~11”)

ALMA Cycle1 (~1’’)

N159W-N

N159W-S

N159E-Papillion
Column Density ※ Derived from 13CO(2-1)

Higher column density in N159E/W
High density core in N159W-North
High density core in N159W-North
GMCs in the Galaxy and LMC

- Massive star forming regions: $>30M_\odot, 10^5L_\odot$
- Similar shapes
  - Filaments + Multiple velocity components
  - Filament-filament interaction?
- Different column density
  - GMCs in the LMC have higher N(H$_2$)
  - More active star formation in the LMC??
1.85m telescope

- $^{12}$CO, $^{13}$CO, $^{18}$O (J=2–1) simultaneously
  - 2SB mixer, Dual pol.
- Beam size: 2.7 arcmin
  - 0.1pc@140pc, 1pc@1-2kpc
- Targets
  - GMCs ($^{12}$CO, $^{13}$CO)
  - Dense cores ($^{18}$O)
  - Comparison with larger radio telescopes, Planck, Fermi, Akari, Herschel
Galactic Plane Survey

Angular resol. high(~arcsec.) low(~arcmin.)

3–2
VST (Hasegawa et al.)
AMANOGAWA (Yoda et al. 2010)

2–1

CfA (Dame et al.)

1–0
Nagoya 4m
NANTEN, NANTEN2 (Fukui et al.)

Mopra, ThrUMMS (Barnes et al. 2015)
NRO45m, FUGIN (Umemoto et al.)

low(~arcmin.) Angular resol. high(~arcsec.)
Galactic Plane Survey

Angular resol. high (~arcsec.) low (~arcmin.)

CfA (Dame et al.) AMANOGAWA (Yoda et al. 2010) VST (Hasegawa et al.)

1–0
CfA (Dame et al.)
Nagoya 4m NANTEN, NANTEN2 (Fukui et al.)

2–1
VST (Hasegawa et al.)
AMANOGAWA (Yoda et al. 2010)

3–2

JCMT, COHRS (北天) (Dempsey et al. 2013)

Osaka 1.85m teles. (This Work!!)

Nagoya 4m NANTEN, NANTEN2 (Fukui et al.)
Mopra, ThrUMMS (Barnes et al. 2015)
NRO45m, FUGIN (Umemoto et al.)

Angular resol.

low (~arcmin.) high (~arcsec.)
Coverage

5 years of operations

- 1st Quad.
  - Ophiuchus
  - Aquila
  - Cygnus
  - GC

- 2nd Quad.
  - Taurus
  - Perseus
  - M31

- 3rd Quad.
  - Outer Galaxy
  - Orion

Back ground: CO (1–0) Dame et al. 2001
Gray: 2010~2013
Color: 2014~

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Area covered</td>
<td>~1450 square degrees</td>
</tr>
<tr>
<td>Ang. reso.</td>
<td>~ 3’</td>
</tr>
<tr>
<td>Grid size</td>
<td>1’</td>
</tr>
<tr>
<td>RMS noise</td>
<td>~ 0.45 K (@dv ~ 0.3 km/s)</td>
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1.85m telescope → Chile

- TAO facility in San Pedro de Atacama (@2500m)
  - ALMA site is expensive!!
- Ultra-wide band receivers (NAOJ + Osaka Pref. Univ.)
  - Band 6 (230GHz)+7 (345GHz) receivers
  - Wide IF: 4-18GHz (→ 4-25GHz)
  - CO(J=2-1, 3-2) simultaneous obs.
- Targets
  - Galactic Plane
  - Magellanic Clouds
High mass SF in GMC

- Resolved CO observations toward GMCs
  - from nearby GMCs to GMCs in the LMC
    - from small telescopes to ALMA
  - a lot of samples with resolutions of $\sim 0.1 \text{pc}$
    - along the galactic plane and in the Magellanic Clouds
  - Dynamical interaction of the gas is a key to understand the high mass star formation.