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

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M. Meixner (STScI), M. Sewiło, O. Nayak (J. Hopkins Univ.), R. Indebetouw (Univ. of Virginia), and many others

ALMA Image: N159W
GMC as a site of high-mass star formation

From galaxy evolution to individual star formation

kpc

1-100pc

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

Wide range of scales
Various distances
Use of various telescopes

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

$<\sim 1$ pc

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 $a \sim 10\text{km/s}$)
    - 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.
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°
Interaction of clouds: Cloud-Cloud collision

- Multiple velocity components are frequently seen toward high-mass star forming regions
  - Dynamics of gas is a key for high-mass star formation
- Increase Jeans mass, compression of gas
- Frequency?
  - can be large
    - No. of GMCs $\sim 10^5$ (Kwan 1979)
    - Mean free time $\sim 10^{\text{Myr}}$: one collision within its lifetime
- Small scale (dense clumps) collision
Massive star cluster formation by CCC

- All of the known four young massive star clusters (MSC) having nebulosity are each associated with two clouds.
- The velocity separations between two clouds are typically 10–20 km/s.
- MSC formation by CCC.
- Time scale of CCC and MSC formation can be estimated as < ~0.5 Myrs.
NGC3603 star formation is quick, in $10^5$ yrs

Fukui et al. 2014

Kudryavtseva et al. 2012

Figure 4. Normalized $L(t)$ for NGC 3603 YC at DM = 14.1 mag. The most probable age is 2.0 Myr. The red curve is a fitted Gaussian function.
Massive star formation by cloud-cloud collision

Cloud-cloud collision (CCC) can induce strong compression of the gas, leading high-mass star formation.

Theoretical work:
- CCC can increase mass accretion rate by more than 100 times than that in the low-mass star formation → leading formation of massive clump/core.

\[
\dot{M} \sim \frac{M_{J,\text{eff}}}{t_{ff}} \sim \frac{(c_s^3 + c_A^3 + \Delta v^3)}{G} \quad (c_s^3 : c_A^3 : \Delta v^3 = 1 : 125 : 90)
\]

\[
M = 5 \times 10^{-4} - 4 \times 10^{-3} \quad M_{\text{Sun/yr}}
\]
Sites of the massive star formation by CCC

- Single O star formation
  - M20
  - Spitzer bubbles (RCW120, RCW145, etc.)
  - UCHII region (Poster by A. Ohama: S316.p94)
- Galactic mini-starbursts
  - NGC6334+NGC6357 (Poster by K. Torii)
  - W49 (Kiridoshi+2015, in prep.)
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: mass, density, temperature dependent
- Detecting distant GMCs at >10kpc

Angular resolution: 3 arcmin

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- Osaka 1.85m at NRO: 12CO(2-1), 13CO(2-1), C$_{18}$O(2-1), Northern sky

Angular resolution: better than ~1'

- FCRAO 14m: 13CO(1-0), $L>18\,\trumillion\,M_{\odot}$, |b|<1
- Mopra 22m: 12CO(1-0), 13CO(1-0), C$_{18}$O(1-0), $L>300\,\trumillion\,M_{\odot}$, |b|<0.5°
- JCMT 15m: 12CO(3-2), $L>28\,\trumillion\,M_{\odot}$, |b|<0.5°
- NRO 45m: 12CO(1-0), $L>198\,\trumillion\,M_{\odot}$, |b|<1°, r=3kpc, r=10kpc
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NRO Galactic Plane Survey

- Using multi-beam receiver FOREST, OTF mapping of the Galactic plane in $^{12}\text{CO}(1-0)$, $^{13}\text{CO}(1-0)$, $^{C^{18}}\text{O}(1-0)$, simultaneously

Mapping area:
- **inner disk**: $l = 10^\circ \sim 50^\circ$ \ $|b| \leq 1^\circ$
  - Spiral arms, interarm, bar/barend
- **outer disk**: $l = 198^\circ \sim 236^\circ$ \ $|b| \leq 1^\circ$
  - Comparison with inner disk
CO three lines

R $^{12}\text{CO}(1-0)$, G $^{13}\text{CO}(1-0)$, B $^{18}\text{O}(1-0)$

~JCMT CO(3-2) resolutions
Survey with <20" resolutions

★ NRO (J=1-0), IRAM (J=2-1), JCMT (J=3-2)
★ Spatial resolution
  ✥ 0.3pc at 3kpc
    - Can spatially resolve dense cores
  ✥ 1pc at 10kpc
    - Can detect dense cores
★ Velocity structures of Herschel and Spitzer distribution
★ Essential to investigate the nature of the GMCs in the entire Galaxy
Initial condition for Massive SF

- Collision/Interaction process can be one of the main cause of massive stars
  - Line observations are important
- Severe contamination in the Galactic plane
  - Large errors in distance determination

- Extragalactic observations
  - Less contamination, same distances in a galaxy
- Distribution of extended emission
  - ALMA + ACA (Morita array)
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
Examples of Large scale observations

Spitzer survey of the LMC
SAGE: Surveying the Agency of the galaxy’s evolution
(Meixner et al. 2006)

GMCs, dust, YSOs, HII regions, SNRs, AGBs, ...

CO: from 1.2 Kkm/s 1.2Kkm/s intervals
(Fukui et al. 2008)
GMCs & high mass star formation activities in the LMC with ~ 40 pc resolution

- 44 clouds (26%) associated with 82 clusters over a time scale of 7Myr
- 88 clouds (51%) associated with 55 clusters over a time scale of 14Myr
- 39 clouds (23%) associated with 82 clusters over a time scale of 6Myr
- 55 clusters over a time scale of 4Myr

Kawamura et al. (2009)
\[ 2.7 \text{arcmin} = 40 \text{pc} \]
N159

- One of the largest
  Mass: 10^7 Mo
  Size: 220 pc
  Has strongest CO emission
- Active star formation
  Five young clusters
  age < 10 Myr
  (Bica et al. 1996)

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$2.7 \text{arcmin} = 40 \text{pc}$
N159: Most active on-going star formation in the Local Group: Resolving filaments and cloud cores in the LMC

Contour: ASTE 12CO(3-2), 22" = 5pc

Fukui [PI]
Yamamoto
Ohama
Onishi
Kawamura
Minamidani
Inbedetouw
Madden
Galametz
Lebouteiller
N.Mizuno
R.Chen
Seale
Sewio
Meixner

Y. Mizuno et al. 2010
ALMA $^{12}$CO(2-1) Integrated intensity [Jy/beam km/s]

ASTE $^{12}$CO(3-2) Integrated intensity [K km/s]

N159 W

1".2 $\times$ 0".8 = 0.29 $\times$ 0.19 pc beam size  

22" = 5 pc
Outflow from massive YSO

\[ \text{13CO}(2-1) \]

Image: Continuum
Red, Blue: Outflow

Blue Component

Red Component
13CO(2-1)

Outflow from massive YSO

Image: Continuum
Blue: Outflow

Blue Component

Graph showing velocity vs. intensity.
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
Star formation in N159W [ALMA cycle1]

- Colliding (Merging?) filaments
  - Width: 1pc
  - Velocity difference: 2-5 km/s
  - Total velocity width: ~ 8km/s
  - Time scale: 6 x 10^4yrs

- Massive YSOs at the intersection
  - Outflow: Mass is infalling (~10^4yrs)
  - Mass accretion rate: 37Mo/6 x 10^4yrs=6x10^{-4}Mo/yr
  - Radio recombination lines: No
  - Massive stars are formed rapidly after the collision

Fukui et al. (2015)
N159: Most active on-going star formation in the Local Group: Resolving filaments and cloud cores in the LMC

Contour: ASTE 12CO(3-2), 22" = 5pc

Y. Mizuno et al. 2010
N159E

12CO(2-1)

Papillon nebula
(Compact HII region: 50Mo star?)
N159 East Papillon

Black Contour: 12CO(2-1)
White Contour: 98GHz Continuum (free-free)
Magenta Contour: H30α

White Contour: 12CO(2-1)
Yellow dashed Contour: 231GHz Continuum (thermal)
Three velocity components?

Blue: 228km/s - 232km/s
Green: 232km/s - 334km/s
Red: 235km/s - 240km/s

Filaments are merging at Papillon
CO gas is rapidly dissociated by the high-mass star
Similar, but more complex velocity structure compared with the N159W filaments
ALMA observations
N159 in the LMC

- Full of Filaments and Arcs
  - Complex velocity structures
- Molecular outflows
  - Dust continuum/Radio Recombination Lines
- Some filaments are colliding/merging
  - Leading to rapid high-mass star formation

Outflow
37Mo YSO
High-mass star formation: Orion in the Galaxy/N159 in LMC

- Size-scale: similar
- Multiple velocity components
  - $dv \sim 10\text{km/s}$
  - Mostly filaments
- Collision process can be one of the main causes of massive stars
- Much higher column density in N159
  - More active star formation in the LMC?
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 a few x 0.1pc
    - along the galactic plane and in the LMC
  - Dynamical interaction of the gas is a key to understand the high mass star formation.
ALMA Image: N159W
Massive YSOs (~30Mo)