Shocked Molecular Clouds in the LMC SNR N132D Revealed by ALMA ACA

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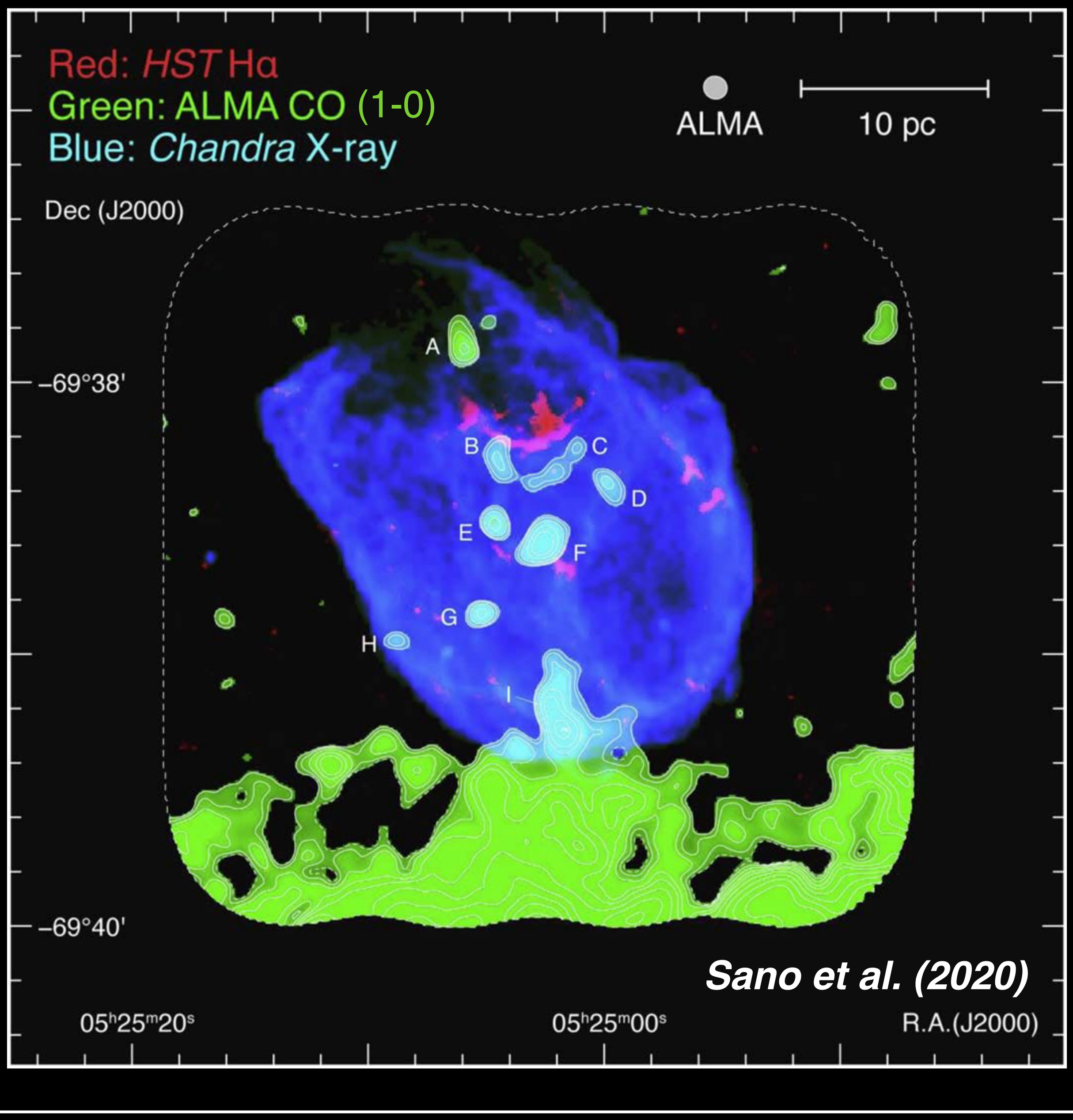
Abstract

Supernova remnants (SNRs) play a crucial role in galaxy evolution due to their energetic shocks and metal enrichment. Especially, shock-cloud interactions are highly related not only to cosmic-ray acceleration but also to star formation rate (e.g., Kortgen et al. 2016). We aim to investigate the universality of physical processes resulting from shock-cloud interactions. SNR N132D is the most suitable target for investigating various shock-cloud interactions. N132D is the most luminous SNR in the local group and is located at the Large Magellanic Cloud (LMC). A well-known distance and little contamination made it easy to accurately estimate the physical properties of molecular clouds associated with N132D. In the present study, we analyzed the latest ^{12}CO (J = 3-2) data obtained with ALMA (ID: 2021.2.00008.S), which has about two times higher angular resolution (corresponding to < 1 pc) and sensitivity. As a result, we identified twice as many clouds associated with N132D. We further made a ^{12}CO (J = 3-2) / ^{12}CO (J = 1-0) ratio map at pc-scale and found that the ratio is higher in the X-ray shell interior and lower in the shell exterior. This trend is consistent with Sano et al. (2020), suggesting that the clouds in the shells interior correspond to post-shock regions. Based on the spatial distribution, temperature, and density of the interstellar clouds, we plan to extract spectra for each small spatial region and evaluate the mechanisms of thermal and nonthermal X-ray emissions.

Supernova remnant N132D in the Large Magellanic Cloud (LMC)



- Core-collapse supernova
  e.g., Yamaguchi et al. 2014; Sharda et al. 2020
- Diameter: ~25 pc (114" × 90")
  e.g., Bozzetto et al. 2017
- Age: ~2500 years
  e.g., Vogt & Dopita 2011; Law et al. 2020
- **Oxygen-rich Ejecta**
  e.g., Lasker 1978; Blair et al. 2000
- Brightest in **thermal X-rays** and GeV gamma-rays
  e.g., Acero et al. 2020
- Detection in TeV Gamma-rays:
  Non-thermal X-ray flux: $F_{2\text{-}10\ \mathrm{keV}} < 2.0 \times 10^{35}$ erg s^{-1}
  → High likelihood of proton-origin gamma rays
  H.E.S.S. Collaboration 2015, 2021; Bamba et al. 2018
- Recombining plasma (RP)
  Bamba et al. 2018; Hitomi Collaboration 2018
- **Association of Molecular Clouds**
  Banas et al. 1997; Sano et al. 2015, 2017, 2020

Aim of the present study

To understand the physical processes due to shock-cloud interactions, we quantify the physical properties of the molecular clouds associated with N132D.

Method

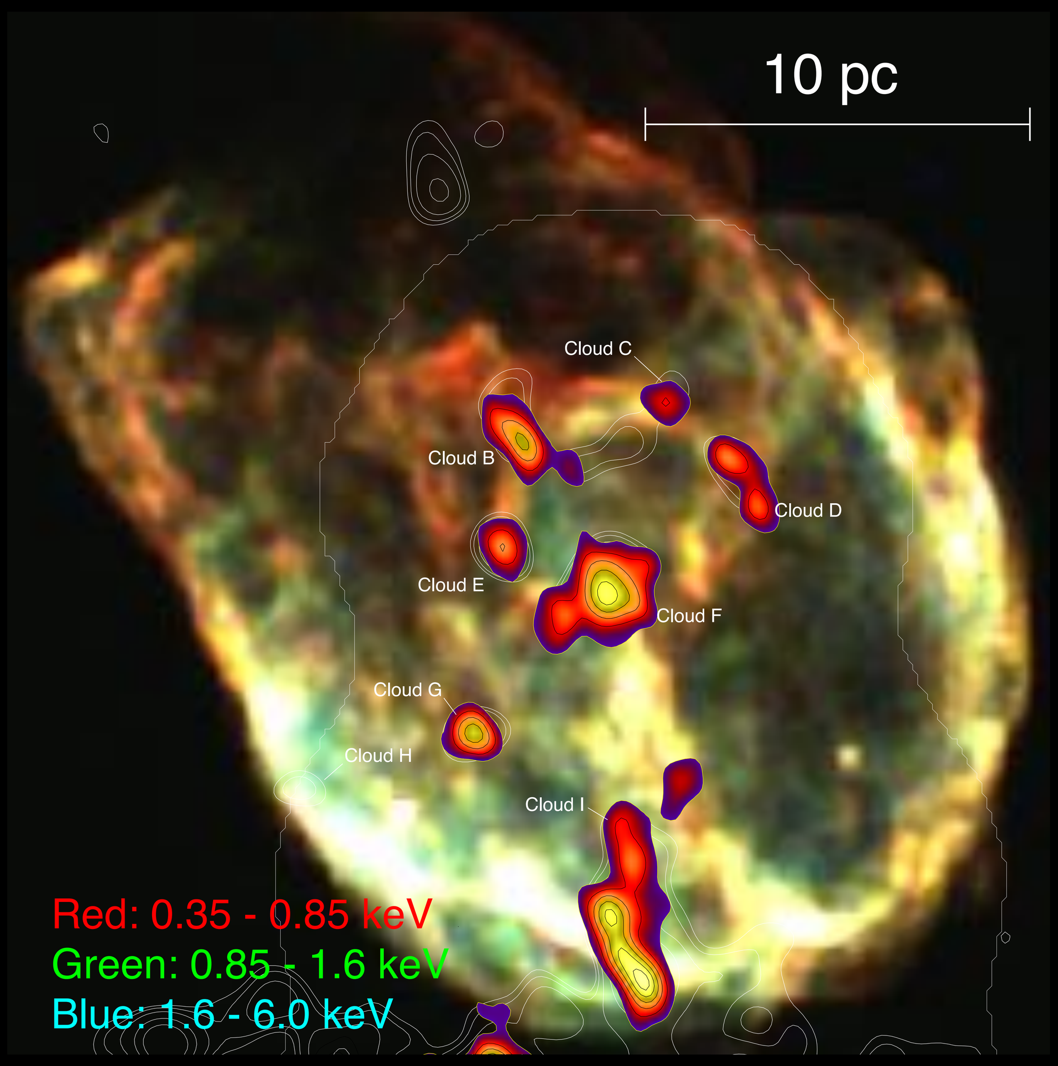
Using ALMA observations of ^{12}CO(J=3-2) with approximately twice the resolution and sensitivity of ^{12}CO (J=1-0)

- Identification of molecular clouds
- Investigating 3-2/(1-0) ratio map to identify shock heating regions.

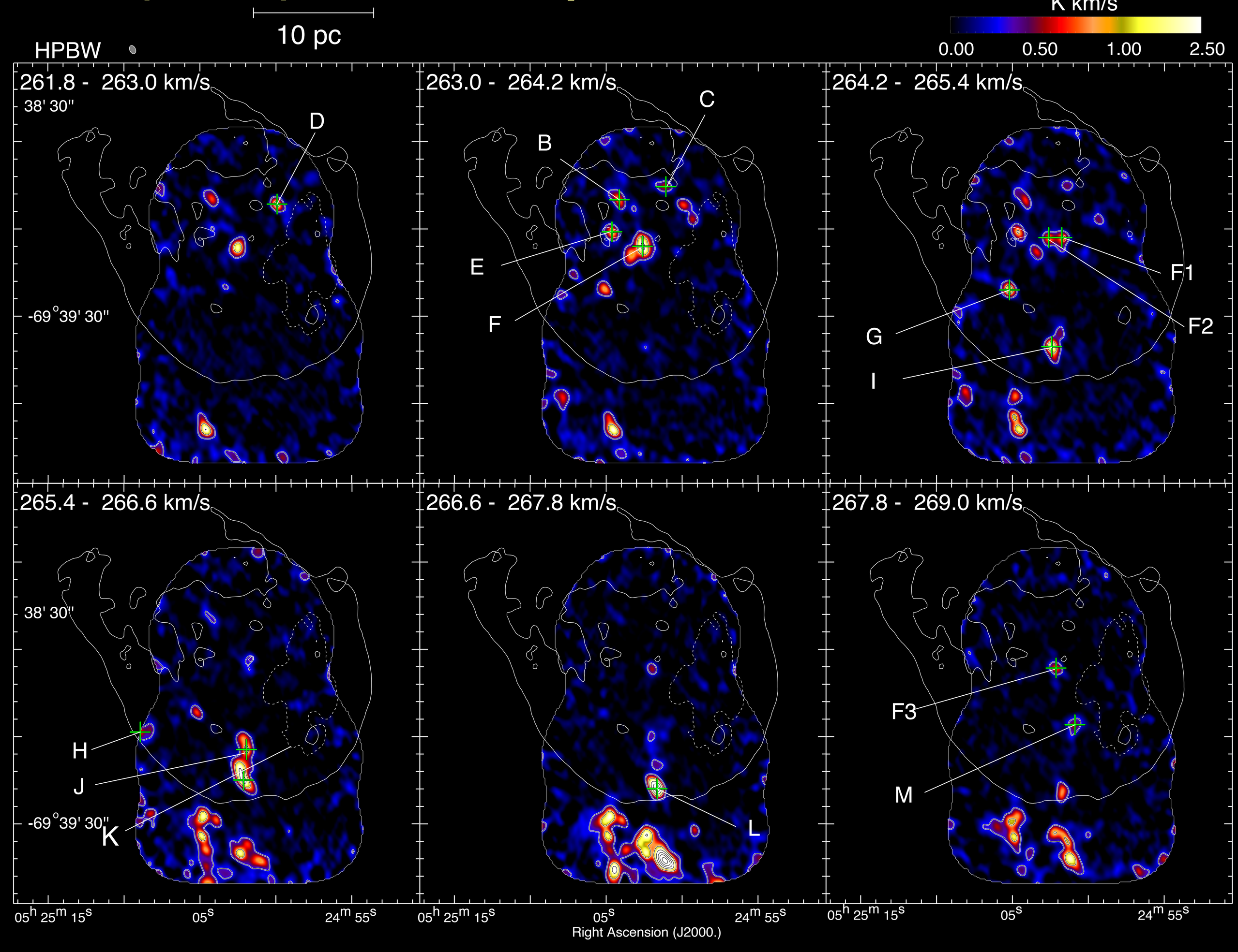
Observation with ALMA

Project #	2021.2.00008.S	2021.2.00008.S
Band /line	Band 7 / CO (J = 3-2)	Band 3 / CO (J = 1-0)
Beam size	~3.8" x 2.7" (~0.8 pc)	~5.3" x 5.0" (~1.3 pc)
RMS noise	~ 0.12 K @0.2 km/s	~ 0.22 K @0.4 km/s

Detection of Clumpy Molecular Clouds on sub-pc scales by ALMA



^{12}CO (J=3–2) channel maps



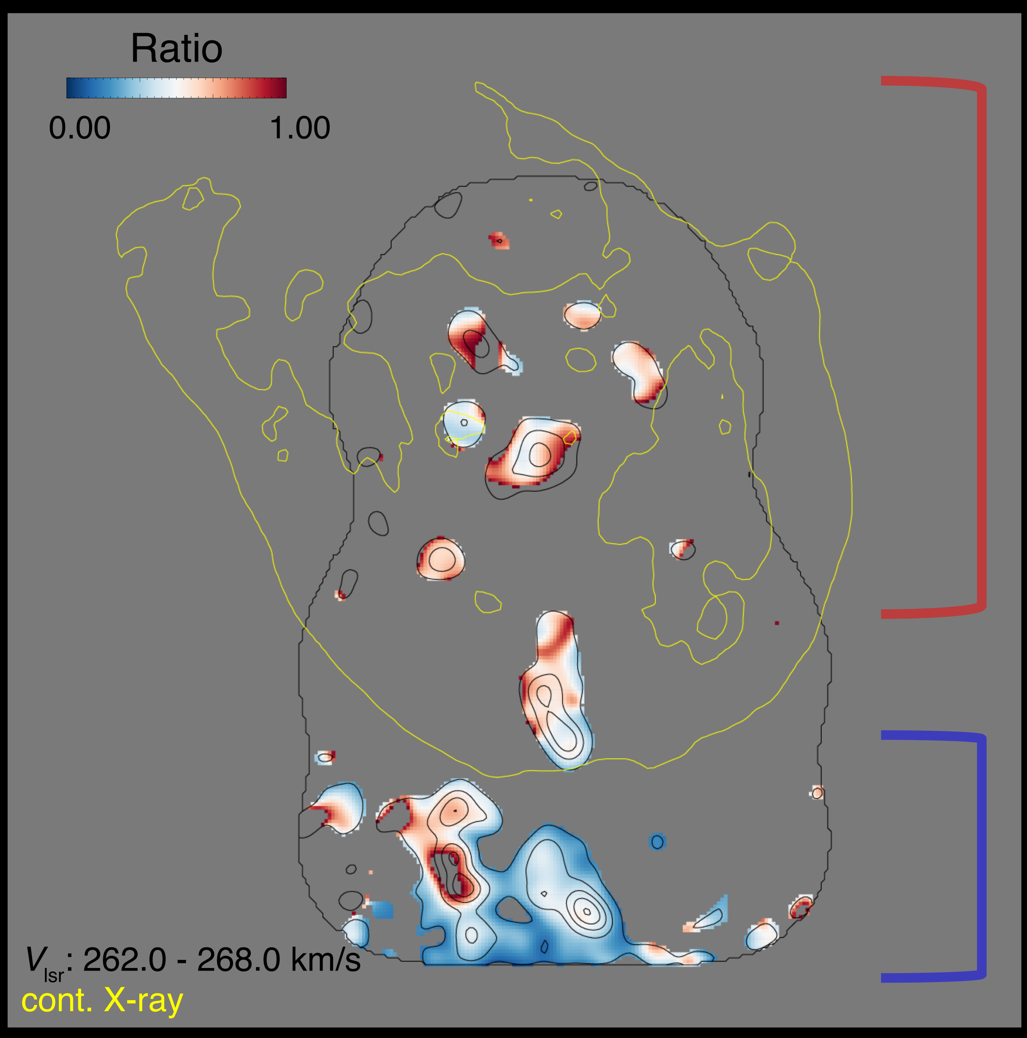
Sixteen clouds were identified, representing an increase of nine from previous studies.

Physical properties of ^{12}CO (J=3–2) clumps

ID	T_R* [K]	V_{peak} [km/s]	ΔV [km/s]	Size [pc]	M_{vir} [Msun]	3-2/1-0	Sano+20
B	0.9	263.7	4.0	1.2	1770	**~1.6**	Clump B
C	0.8	263.7	1.8	1.1	340	~0.8	Clump C
D	1.5	262.7	1.6	1.0	230	~0.5	Clump D
E	1.7	264.2	1.5	1.0	200	~0.4	Clump E
F	2.4	263.2	1.6	1.3	320	~0.5	Clump F
F1	1.3	265.0	1.3	1.2	180	**~0.9**	Clump F
F2	1.4	264.0	1.9	0.9	320	~0.5	Clump F
G	1.5	264.7	2.4	1.0	520	~0.5	Clump G
H'	1.3	265.7	0.8	1.2	70	~0.5	
I	2.4	265.4	1.7	1.1	310	~0.6	Clump I
J	1.5	265.8	1.3	1.5	230	~0.4	Clump I
K	2.3	266.2	1.8	1.6	500	~0.5	Clump I
L	3.7	267.2	1.4	1.2	200	~0.5	Clump I
M	0.9	269.4	2.6	1.4	910	~0.7	
F3	0.8	268.4	2.9	1.1	910	**~1.1**	Clump F

- Cloud F was decomposed into multiple components, each exhibiting a diverse range of physical properties.

^{12}CO (J=3–2) / ^{12}CO (J=1–0) Ratio map



Large scale trend

- X-ray shell interior
  higher
- X-ray shell exterior
  lower

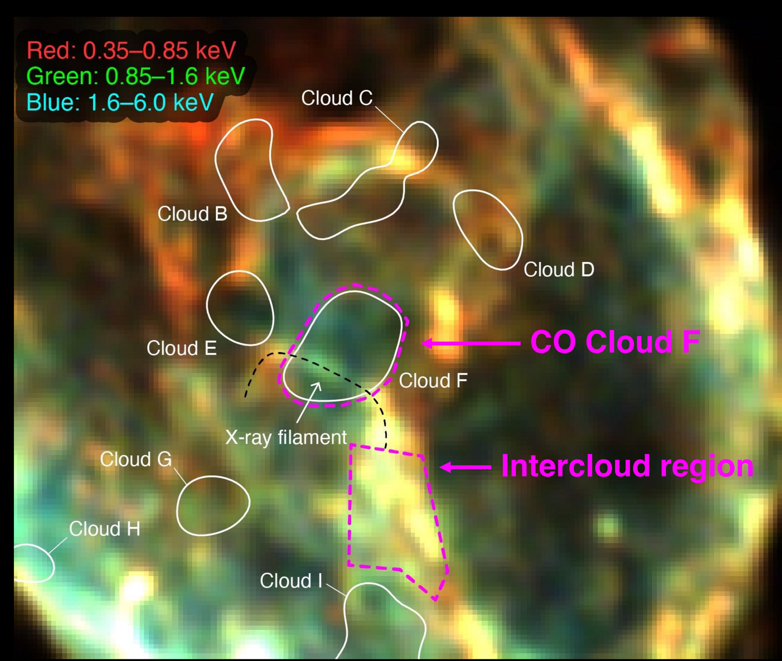
Suggestion

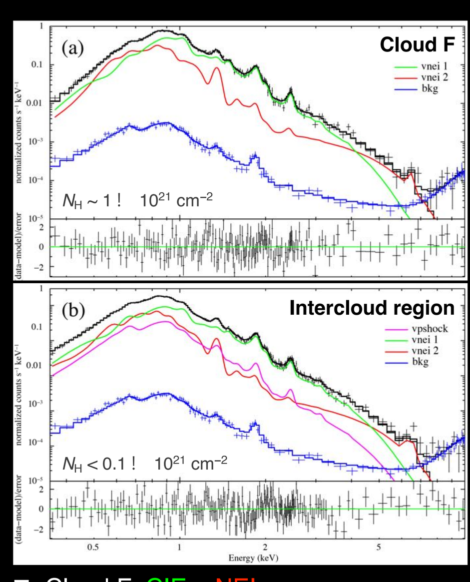
The clouds in the shell interior correspondto post-shock regions.

Each individual cloud exhibits a 3-2/1-0 ratio ranging from 0.4 to 1.6. This variation indicates differing physical conditions and shock-cloud interactions within the shell.

Summary and future prospects

- We identified approximately twice as many clumps associated with the SNR compared to previous studies.
- We found that these clumps exhibit a diverse range of physical properties, such as line widths and 3-2/1-0 ratios.





- Cloud F: CIE + NEI
- Intercloud: CIE + NEI + vpshock

Forward shock has been terminated in Cloud F

The ISM based X-ray spectroscopy is needed

[Japanese KAKENHI grant has been accepted (PI: Sano)]
[Chandra Large proposal has been accepted, (PI: Plucinsky, Co-I: Sano)]