Recent Science Outcome with Radio Astronomical Observatories Operated by NAOJ

Misato Fukagawa

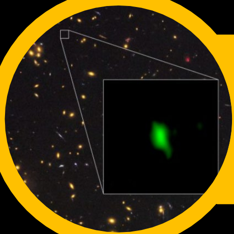
Thanks to K. Tatematsu

VERA/VLBI → Fujisawa-san's talk

December 12, 2019, NAOJ Mitaka

Recent progress obtained with radio facilities

→ Unveiling the hidden Universe
→ Toward statistics, non-biased views
→ Diversity in science, new stream



First stars, cosmic reionization

Galaxy evolution

Star formation

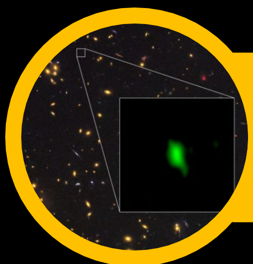
Planet formation, exoplanets

Origin of life

Physics

Chemistry

The Sun → Solar session



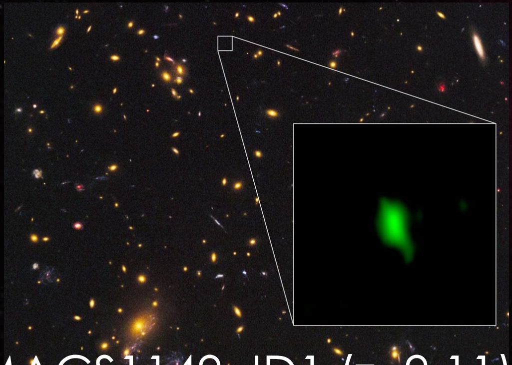
First stars, cosmic reionization

Toward the highest-z objects

When metal enrichment happened?

- [OIII] 88 micron is a promising probe to look back to the first epoch of galaxy formation
- [OIII] and dust at z=8.312 (13.2 G ly) (Tamura et al. 2019)

Suggesting the presence of a past star formation episode as the origin of dust, triggered 0.3 Gyr ago.



MACS1149-JD1 (z=9.11)

Inoue et al. (2016), Laporte et al. (2017), Hashimoto et al. (2018)

Credit: ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al.

Galaxy evolution

Cosmic star formation history

Taking census of the obscured universe at z >3

- Unveiled a dominant population of massive galaxies at z>3 that are invisible in the HST NIR imaging. (Wang et al. 2019)
- They contribute a total star-formation-rate density x10 of equivalently massive UV-bright galaxies at z > 3.

Theory do not predict such a large population of massive and dusty galaxies in the early Universe.

Cosmic star formation history

What is the mechanism to determine SF in the early Universe?

- Morphology of distant starburst, merging galaxies.

Most distant major merger
Hashimoto et al. (2019)

Hodge et al. (2018), Tadaki et al. (2018), Diaz-Santos et al. (2018)

A2744_YD4 (z=8.38)

Cosmic star formation history

What drives the cosmic SF history? Gas content?

Decarli et al. (2019), *Large Program*

- CO luminosity function in the star formation history.
- CI (CO dark gas)
- [CII] measurements in *Large Program*, extended halo, chemistry

See also Fujimoto et al. (2019)

Lensing Cluster Survey in *Large Program* (PI: K. Kohno)

ASTE

ASTE – DESIMA saw the first light in 2019. Redshift survey using DESHIMA to spectroscopically identify ~100 dusty galaxies.

Galaxy evolution

Star formation

NRO

Molecular gas content

In the galaxy-size scale

- ^{12}CO, ^{13}CO, C^{18}O(1—0) for 147 nearby galaxies with 17" resolution. (COMING, Sorai et al. 2019)
- Molecular fraction decreases with stellar mass in early-type galaxies, and vice versa in late-type galaxies.

Study in the GMC scale

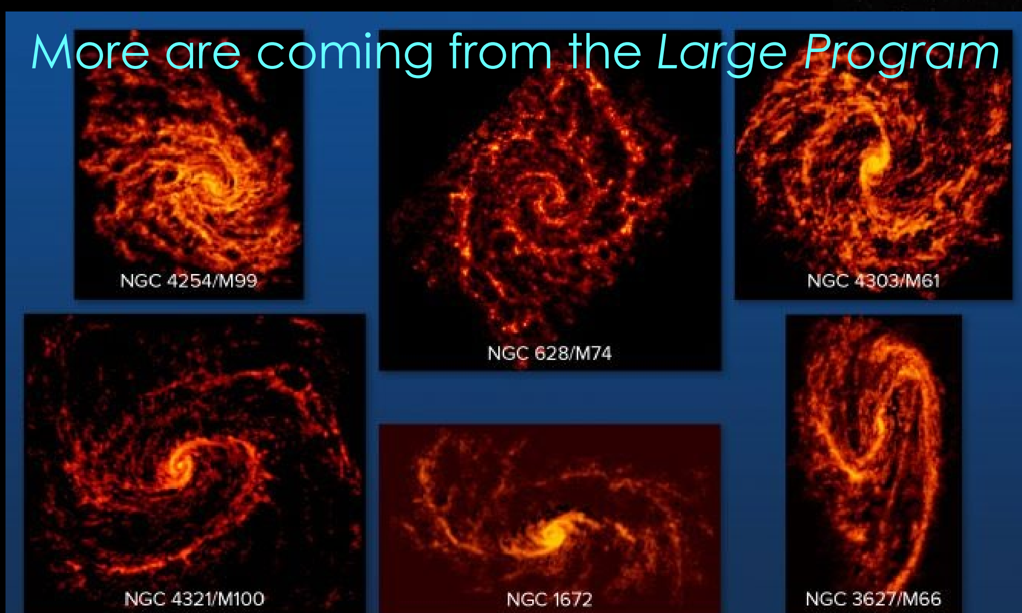
GMC, filamentary cloud study: MW and beyond

- SF rate – galactic dynamics, stellar/AGN feedback, collapse of molecular gas → resolving at smaller scale
- ALMA Large program: CO(2—1) at 1” resolution (~100 pc) for 74 nearby star-forming galaxies → 30,000 GMCs
- Study on the basic molecular cloud properties

star formation is inefficient across disks, clouds have short lifetimes etc.

e.g., Schinnerer et al. (2019)

Tokuda et al. (2019)



Credit: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton

Resolution < 100 pc

NRO

Dense gas mass fraction

In the Milkey Way

- ^{12}CO, ^{13}CO, C^{18}O(1—0) obtained in the FOREST Unbiased Galactic plane Imaging survey (FUGIN)
- First providing the Galactic dense gas fraction = 2.9% over ~5 kpc scale from C^{18}O (Torii et al. 2019)
- Dense gas formation can be the primary factor in inefficient star formation in galaxies

ALMA, NRO

Details on star formation

- Hubs, filaments, clamps for low-mass SFR, super star cluster, and SMC (e.g, Shimajiri et al. 2019, Dobashi et al. 2019)
- Massive binary system formation
- Massive protostellar outbursts
- First hydrostatic core candidates, characterization of dense cores, protobinaries
- BD formation

Brogan et al. (2019)

Zhang et al. (2019)

Planet formation, exoplanets

Formation of planetary systems

- Substructures are ubiquitous for ~Myr stars
- Dust trapping is plausible as a mechanism of planetesimal formation

ALMA Partnership et al. (2015)

Andrews et al. (2018 December), from the *Large Program*

Directions:

- Gas observations are important: gas-to-dust, dynamics, chemistry
- Removing the bias towards large disks
- Younger disks to look for the 1st epoch of planet formation and origin of diversity

→ New *Large Program* (PI: N. Ohashi)

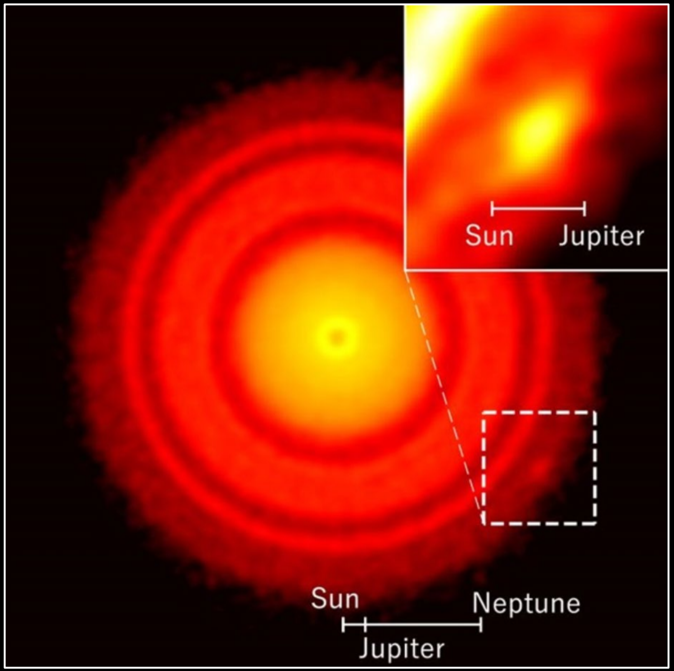
~1 au region

Andrews et al. (2016)

Circumplanetary disks, hint of protoplanets

Isella et al. (2019)

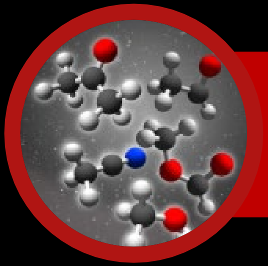
Tsukagoshi et al. (2019)



Credit: ALMA (ESO/NAOJ/NRAO), Tsukagoshi et al.

Teague et al. (2019)

Meridional flows



More on chemical aspects

Origin of life

Chemical complexity

Chemistry to probe physical conditions

- Chemical variations in some nearby galaxies
- Detection of AlO (aluminum monoxide) in the YSO outflow

Tachibana et al. (2019)

ALMA Large Program results are coming for galaxies as well as evolved stars

Harada et al. (2019)

Chemical complexity

Chemistry in star and planet formation

- Organic molecules in planet-forming disks
  Similarity to comets

The volatile composition of comets and planetesimals is partially inherited from the pre- and protostellar phases of evolution.

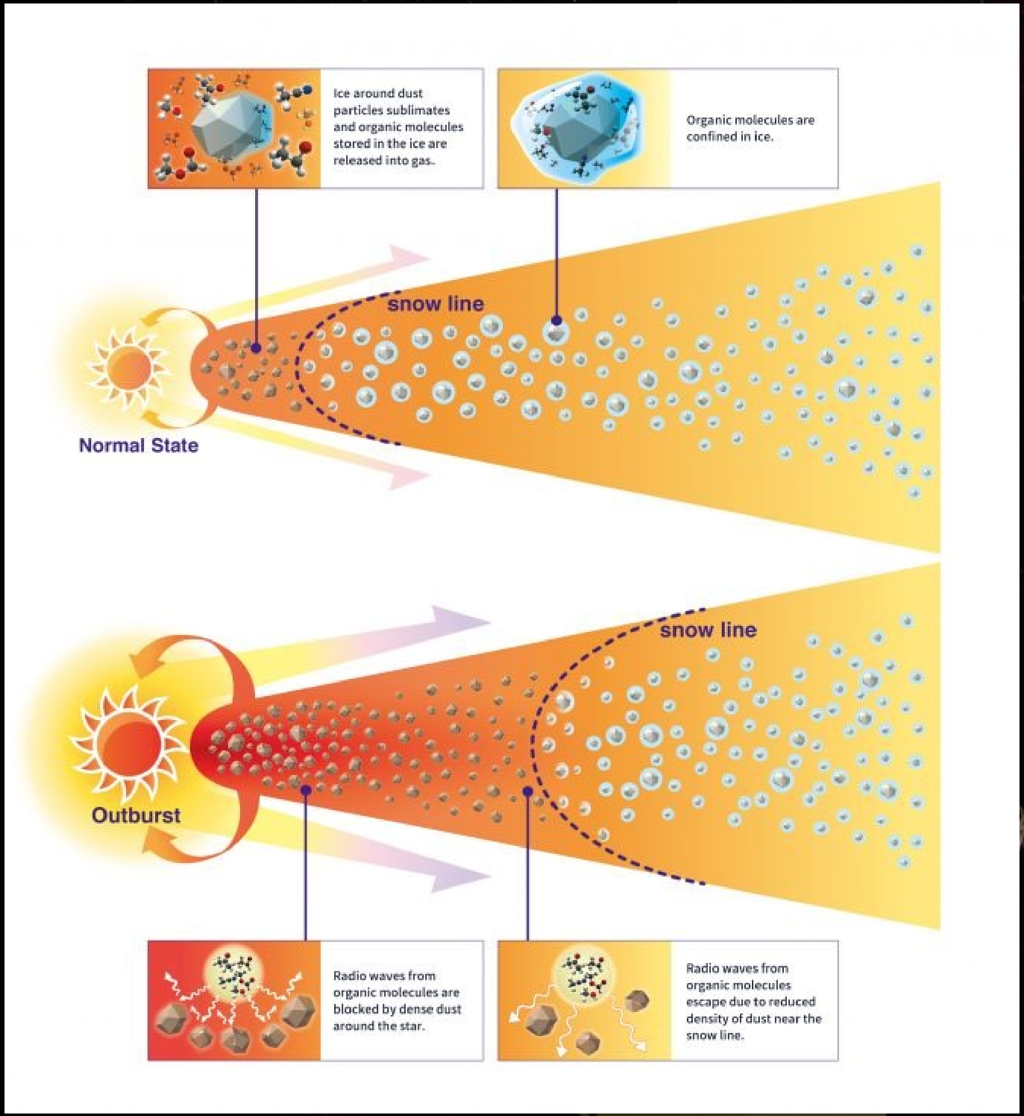
Drozdovskaya et al. (2019)

Large Program results will come
(PI: S. Yamamoto)

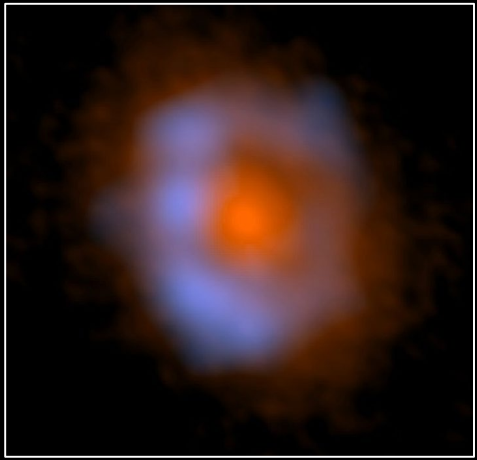
Chemical complexity

Chemistry in star and planet formation

- Detection of complex organic molecules in planet-forming disks



Lee et al. (2019)



Credit: ALMA (ESO/NAOJ/NRAO), Lee et al.

NRO

Unbiased line survey for a protostar

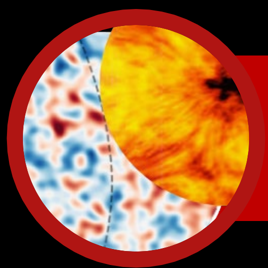
Chemistry in star and planet formation

Consistent with the representative carbon-chain rich starless core.

Yoshida et al. (2019)

- Few survey so far toward warm carbon-chain chemistry sources.
- Good template of a chemical composition of the WCCC source.

Supplementary data taken in the 70 GHz band for fundamental transitions of deuterated species.



More on physical aspects

Also see results on the SZ effect: e.g., Di Mascolo et al. (2019)

VLBI

First image of the possible black hole shadow

- 1.3 mm observation with the Event Horizon Telescope (8 telescopes), ALMA is a part of the 8 telescopes.
- Emission ring with a diameter of 42 ± 3 μ-arcsec, with asymmetric brightness distribution

The EHT Collaboration (2019)

8 stations of the EHT 2017 campaign

VLBI

First image of the possible black hole shadow

- Consistent with the expectation for the shadow of a black hole.
- BH mass estimate: $M=(6.5 \pm 0.7)\times10^{9}\ M_{\odot}$
- Brightness asymmetry: Relativistic beaming of material rotating in the clockwise direction as seen by the observer.

The EHT Collaboration (2019)

Hada et al. (2017)

Polarization, time domain

- Magnetic field
- Grain growth
- First detection of GRB radio polarization (Laskar et al. 2019)
- Detailed morphology of evolved stars

Laskar et al. (2019)

Polarization by scattering of submm emission – new probe for grain size (Kataoka et al.)

Dent et al. (2019), Ohashi et al. (2019), Mori et al. (2019)

Hull et al. (2017)

In the conferences and publications, many other facilities have been mentioned: Swift, Chandra, HST, Spitzer, Herschel, JWST, BLAST, Planck, SOFIA, Subaru, VLT, NOEMA, SMA, CARMA, VLA, ngVLA, AtLAST, GBT, SPT, KVN …

We have seen steps forward to solve long-standing problems

Unveiling the hidden Universe
Toward statistics, non-biased views
Diversity in science, new stream

- *How do galaxies form and evolve?*
- *How do planetary systems form?*
- *How do materials in the Universe evolve and produce the chemical richness with emergence of life?*

- *Many other important topics:*

  high-mass stars/brown dwarfs formation
  coronal/chromospheric heating of the Sun,
  morphology of surrounding material of evolved stars…

Unveiling the hidden Universe
Toward statistics, non-biased views
Diversity in science, new stream

- ALMA – Papers from Large Programs
- Nobeyama – Papers from dedicated surveys, science with deuterated molecules etc.
- ASTE – Band 10, DESIMA science