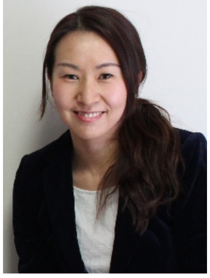
坂井星・惑星形成研究室
Star and Planet Formation Laboratory



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キーセンテンス：

1. 星・惑星系形成過程の研究
2. 星間空間における物質進化の研究
3. 分光実験による分子の回転遷移周波数の精密測定

キーワード：

星間化学、星間分子、電波観測、分光観測、電波干渉計、星形成、惑星系形成

研究概要

「太陽系のような環境はどれほど宇宙で普遍的に存在するのか？」。この問いに答えるには、母体となる星間分子雲から星や惑星がどのように作られるか、という物理進化の理解が不可欠である。同時に、星間分子雲で作られた様々な分子がどのように惑星系へもたらされるか、という化学進化の理解も原始地球環境との関連で非常に重要である。当研究室では、アルマ望遠鏡などの最先端電波望遠鏡を用いて、これらの両面から星と惑星の誕生過程を研究している。また、観測に必要な分子の回転遷移輝線の周波数を精密に測定する分子分光実験の準備も進めている。

Key Sentence :

1. Formation of protostar and protoplanetary disks
2. Tracing chemical processes in interstellar clouds
3. Millimeter- and submillimeter-wave spectroscopy for molecules of astrochemical interests

Key Word :

Astrochemistry, Interstellar Medium, Molecular Cloud, Radio Observation, Spectroscopic Observation, Interferometric Observations, Star Formation, Plotoplanetary Disk

Outline

Star and planet formation is one of the most fundamental structure-formation processes in the universe. By use of the state-of-the-art radio telescopes including ALMA, we are investigating when a disk structure is formed around a solar-type protostar, and how it is evolved into a protoplanetary disk and eventually to a planetary system. This is an essential question deeply related to the origin of the Solar system. We particularly focus on a relation between physical evolution and chemical evolution during star and planet formation. Related laboratory spectroscopic studies in the millimeter and submillimeter regimes are also planned.

Overview

Star and planet formation is one of the most fundamental structure-formation processes in the universe. By use of the state-of-the-art radio telescopes including ALMA, we are investigating when a disk structure is formed around a solar-type protostar, and how it is evolved into a protoplanetary disk and eventually to a planetary system. This is an essential question deeply related to the origin of the Solar system. We particularly focus on a relation between physical evolution and chemical evolution. Star and planet formation is a process where interstellar matter is evolved into planets. Hence, chemical approach tells us not only chemical evolution itself but also novel information on physical processes of star and planet formation. Furthermore, such a chemical study is of fundamental importance in understanding an origin of the solar system, and eventually an origin of life on the Earth. With these in mind, we are studying star and planet formation by radio observations from chemical point of view. At the same time, we have started laboratory spectroscopy in millimeter band to tera-helz band to directly measure rest frequencies of rotational transitions of molecules with astronomical interest. With ALMA, we can observe huge number of spectral lines of molecules in star and planet forming regions. A large fraction of them is unidentified. Even for the identified lines, rest frequencies in the databases are sometimes not enough for Doppler analysis to understand the kinematics of the molecular gas. Thus, accurate measurement of the rest frequencies are essential for the current astronomy.

Project A：Chemical Diversity in Star and Planet Forming Region

A comprehensive understanding of chemical evolution from protostellar cores to protoplanetary disks is important in relation to the origin of the Solar-System environment, which can eventually be related to origin of life. So far, it has been established that chemical composition of the protostellar cores shows significant chemical diversity. One distinct case is the hot corino chemistry, which is characterized by rich existence of saturated organic molecules. The other distinct case is the warm carbon-chain chemistry (WCCC), which is characterized by rich existence of unsaturated organic molecules such as carbon-chain molecules. It is proposed that a duration time of the starless core phase would cause this diversity. In this FY, we have statistically studied the core scale (a few 1,000 au) diversity in one giant molecular cloud complex, and revealed the possible origin. More interestingly, how is this chemical diversity brought into protoplanetary disks and planetary systems? With ALMA, we revealed that such diversity is certainly delivered to the disk forming region with size scale of 100 au. We have also investigated the possible tracer of the cloud chemical age, DNC/HNC ratio.

Project B：Star and Planet Formation

By full use of chemical tool, we have revealed how dense cores are formed and how disks are formed inside the cores. We have also obtained a hint to the question; how protoplanetary disks evolve into matured system. Chemistry reflects not only history of physics, but also small changes in physical condition. It brings the breakthroughs to study physical evolution, such as disk formation, outflow launching, and planet formation. We thus further extended such methods especially on structure formation inside the disks, on disk formation around different mass protostars (high mass and very low-mass), and star formation in other nearby galaxies.

Project C：Development of Spectrometer and Spectroscopy

We have succeeded to launch the accurate (10^{-12} order) and wide frequency band spectrometer (8 GHz at a time) by using radio-observation technique, which is new method, and have succeeded the test measurements. We are ready for full-scale operation. Furthermore, we have tested a possibility to install Tera-Helz direct spectroscopy by using hot electron bolometer mixer.

Highlights of Project A

A-1: Chemical Diversity and its' origin (Ref. paper 6, led by Aya Higuchi)

The chemical diversity of gas in low-mass protostellar cores is widely recognized. In order to explore the origin of this diversity, a survey of chemical composition toward 36 Class 0/I protostars in the Perseus molecular cloud complex, which are selected in an unbiased way under certain physical conditions, has been conducted with IRAM 30 m and NRO 45 m telescope. Multiple lines of C_2H, c-C_3H_2, and CH_3OH have been observed to characterize the chemical composition averaged over a 1000 au scale around the protostar. The derived beam-averaged column densities show significant chemical diversity among the sources, where the column density ratios of C_2H/CH_3OH are spread out by two orders of magnitude. From previous studies, the hot corino sources have abundant CH_3OH but deficient C_2H, their C_2H/CH_3OH column density ratios being relatively low. In contrast, the warm-carbon-chain chemistry (WCCC) sources are found to reveal the high C_2H/CH_3OH column density ratios. We find that the majority of the sources have intermediate characters between these two distinct chemistry types. A possible trend is seen between the C_2H/CH_3OH ratio and the distance of the source from the edge of a molecular cloud. The sources located near cloud edges or in isolated clouds tend to have a high C_2H/CH_3OH ratio. On the other hand, the sources having a low C_2H/CH_3OH ratio tend to be located in the inner regions of the molecular cloud complex. This result gives an important clue toward understanding the origin of the chemical diversity of protostellar cores in terms of environmental effects. We have also tested whether deuterium fractionation ratio of neutral species such as DNC/HNC can trace chemical youth, i.e. time after the UV shielding. In cold starless clouds, it is generally known that molecular D/H ratio increases by time after the UV shielding of the parent cloud. The fractionated D/H ratio of neutral species keeps a while, although the deuterium fractionation of ionic species are cancelled easily. However, contrary to the expectations, the deuterium fractionation in HNC is also cancelled. HNC is early time species and hence, it can easily be converted to HCN in dense conditions. Then, dense and warm regions are hardly traced. Rather, DNC/HNC ratio well anticorrelate with the bolometric temperature of the sources. (See Ref. paper 19 as well)

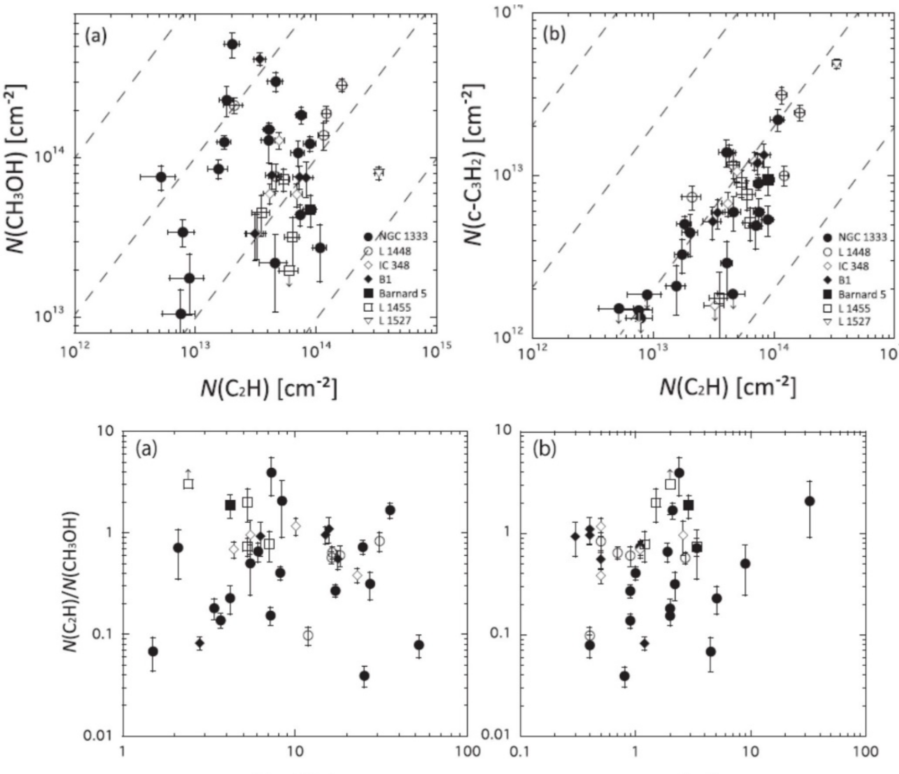


Fig. 1

Chemical diversity in young stellar object located in Perseus molecular cloud complex. (top-a) CH_3OH and C_2H abundance ratios show significant diversity (more than 2 orders of magnitude). (top-b) C_2H and c-C_3H_2 abundances are well correlated. (bottom-a) The ratio does not correlate with the envelope mass of the protostars. (bottom-b) The ratio does not crelate with the bolometric luminosities of the sources.

A-2: Discovery of Gravitationally Unstable Condensations just before Star Formation -Revealing the CH$_3$OH formation mechanism in cold starless cloud-- (Ref. paper 1, led by Satoshi Ohashi)

We have investigated the TUKH122 prestellar core in the Orion A cloud using ALMA 3 mm dust continuum, N2H+ (J=1−0), and CH3OH (JK=2K-1K) molecular-line observations. Previous studies showed that TUKH122 is likely on the verge of star formation because the turbulence is almost dissipated and chemically evolved among other starless cores in the Orion A cloud. By combining ALMA 12 m and ACA data, we recover extended emission with a resolution of ~5″ corresponding to 0.01 pc and identify six condensations with a mass range of 0.1–0.4M. and a radius of ~0.01 pc. These condensations are gravitationally bound following a virial analysis and are embedded in the filament, including the elongated core with a mass of ~29M. and a radial density profile of r−1.6 derived by Herschel. The separation of these condensations is ~0.035 pc, consistent with the thermal Jeans length at a density of 4.4×105 cm−3. This density is similar to the central part of the core. We also find a tendency for the N2H+ molecule to deplete at the dust peak condensation. This condensation may be beginning to collapse because the line width becomes broader. Therefore, the fragmentation still occurs in the prestellar core by thermal Jeans instability, and multiple stars are formed within the TUKH122 prestellar core. Toward this evolved starless core, just before the star formation, the CH3OH emission shows a large shell-like distribution and surrounds these condensations. This suggests that the CH3OH molecule formed on dust grains is released into the gas phase by nonthermal desorption such as photoevaporation caused by cosmic-ray-induced UV radiation.

Highlights of Project B

Observations of molecular line emission allowed to trace the gas accretion from the envelope to the disk, and the details of the conditions of the gas around the centrifugal barriers. Angular momentum transfer from the envelope/disk to the outflow could also be investigated by selecting appropriate molecular line tracers. Here we introduce several examples.

B-1: Launching point of the low velocity outflow (Ref. paper 15, led by Yichen Zhang)

Toward NGC 1333 IRAS 4C outflow in the Perseus Molecular Cloud, the CCH and CS emission reveal an outflow cavity structure with clear signatures of rotation with respect to the outflow axis. The rotation is detected from about 120 au up to about 1400 au above the envelope/disk midplane. As the distance to the central source increases, the rotation velocity of the outflow decreases while the outflow radius increases, which gives a flat specific angular momentum distribution along the outflow. The mean specific angular momentum of the outflow is about 100 au km s-1. On the basis of reasonable assumptions on the outward velocity of the outflow and the protostar mass, we estimate the range of outflow-launching radii to be 5–15 au. Such a launching radius rules out that this outflow is launched as an X-wind, but rather, it is more consistent to be a slow disk wind launched from relatively large radii on the disk.

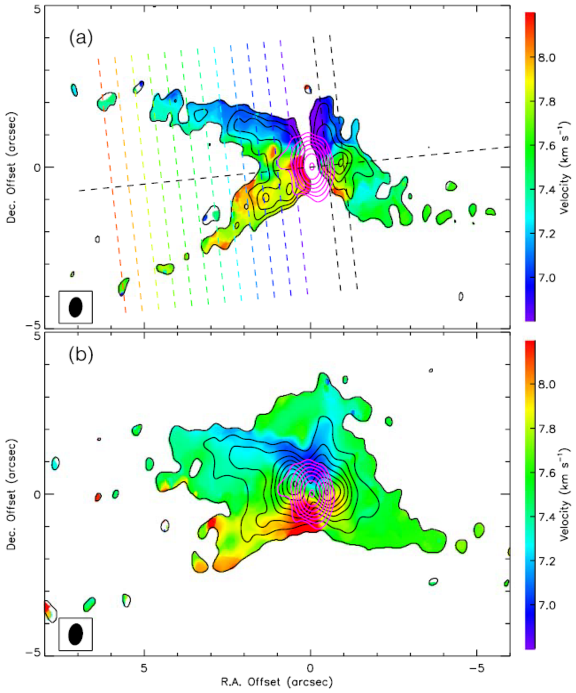


Fig.2 Integrated intensity maps of CCH(top, contours) and CS(bottom, contours) and their velocity field structure (color).

B-2 Coevolution of a protostar and the disk (Ref. paper16)

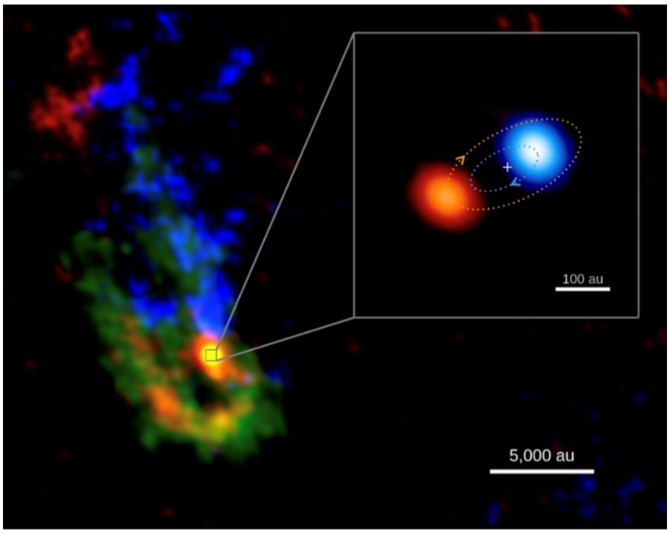
We have observed the CCH and SO line emission at a 0.2” angular resolution toward the low-mass Class 0 protostellar source IRAS 15398–3359 with ALMA. The CCH emission traces the infalling-rotating envelope near the protostar with the outflow cavity extended along the northeast southwest axis. On the other hand, the SO emission has a compact distribution around the protostar. The CCH emission is relatively weak at the continuum peak position, while the SO emission has a sharp peak there. Although the maximum velocity shift of the CCH emission is about 1 km s^{-1} from the systemic velocity, a velocity shift higher than 2 km s^{-1} is seen for the SO emission. This high-velocity component is most likely associated with the Keplerian rotation around the protostar. The protostellar mass is estimated to be $0.007^{+0.003}_{-0.004}$ M. from the velocity profile of the SO emission. With this protostellar mass, the velocity structure of the CCH emission can be explained by the model of the infalling-rotating envelope, where the radius of the centrifugal barrier is estimated to be 40 au from the comparison with the model. The disk mass evaluated from the dust continuum emission by assuming the dust temperature of 20–100 K is 0.1–0.9 times the stellar mass, resulting in the Toomre Q parameter of 0.4–5. Hence, the disk structure may be partly unstable. All these results suggest that a rotationally supported disk can form in the earliest stages of the protostellar evolution.

B-3 Drastic chemical change could also be used to trace disk formation around massive protostars (Ref. paper 26, led by Yichen Zhang)

We investigated molecular line observations of the massive protostellar source G339.88-1.26 with ALMA. The observations reveal a highly collimated SiO jet extending from the 1.3 mm continuum source, which connects to a slightly wider but still highly collimated CO outflow. Rotational features perpendicular to the outflow axis are detected in various molecular emissions, including SiO, SO_2, H_2S, CH_3OH, and H_2CO emissions. Based on their spatial distributions and kinematics, we find that they trace different parts of the envelope–disk system. The SiO emission traces the disk and inner envelope in addition to the jet. The CH_3OH and H_2CO emissions mostly trace the infalling-rotating envelope and are enhanced around the transition region between envelope and disk, i.e., the centrifugal barrier. The SO_2 and H_2S emissions are enhanced around the centrifugal barrier and also trace the outer part of the disk. Envelope kinematics are consistent with rotating-infalling motion, while those of the disk are consistent with Keplerian rotation. The radius and velocity of the centrifugal barrier are estimated to be about 530 au and 6 km s-1, respectively, leading to a central mass of about 11M., consistent with estimates based on spectral energy distribution fitting. These results indicate that an ordered transition from an infalling-rotating envelope to a Keplerian disk through a centrifugal barrier, accompanied by changes of types of molecular line emissions, is a valid description of this massive protostellar source. This implies that at least some massive stars form in a similar way to low-mass stars via core accretion.

B-4 Revealing dynamics of a massive binary at birth (Ref. paper 28, led by Yichen Zhang)

We discovered a binary star system composed of two massive stars that are still in the act of formation. We used the most powerful observing mode of ALMA resolve these protostars as having an apparent separation of 180 au, about three times the diameter of Neptune’s orbit around our Sun. We also measured the motions of the stars, determining that their total mass is at least 18 M., with the primary having at least 10 M., and one full orbit is completed in no more than 600



years. These are the first such constraints for a forming high-mass binary, which provide critical insights for understanding the birth of massive stars. Massive stars are important throughout the universe, not least for producing the heavy elements that make up our Earth and are in our bodies. However, their formation is literally shrouded in mystery, being so deeply embedded in dusty clouds where they are born. This work also represent that kinematic structures of disk forming region around massive stars could be investigated by using hydrogen recombination lines.

B-5 Early protostar already has a warped disk (Ref. paper 21)

Recent advances on exoplanet studies have revealed that orbital planes of planets are not always aligned with one another or with the equatorial plane of the central star. The misalignment has been ascribed to gravitational scattering by giant planets and/or companion stars. On the other hand, there is an alternative idea that the misalignment is natal: i.e., such planets were born in a warped protostellar disk. The warped disk structure is in fact reported in some transition disks and protoplanetary disks. In contrast, it has not been detected in the earlier stages, although such a possibility is implicated from the outflow morphology. Based on the dust continuum observation with ALMA, we have discovered a warped infant disk, which is still growing around the Class 0 protostar, IRAS04368+2557. The disk consists of inner and outer parts with slightly different orbital planes, which are connected at 40-60 au in the radius from the protostar. In addition, the warp structure has the point-symmetry within a radius of ~80 au. This fact indicates that the warp structure exists in a rotationally supported disk. Since there is no evidence of the association of heavy companion sources, the warp structure can be due to the anisotropic-accretion of the gas having different rotation axes or the misalignment of the rotation axis of the disk and the magnetic field direction. Our result shows a direct evidence that the disk-formation process can cause diversity in planetary systems.

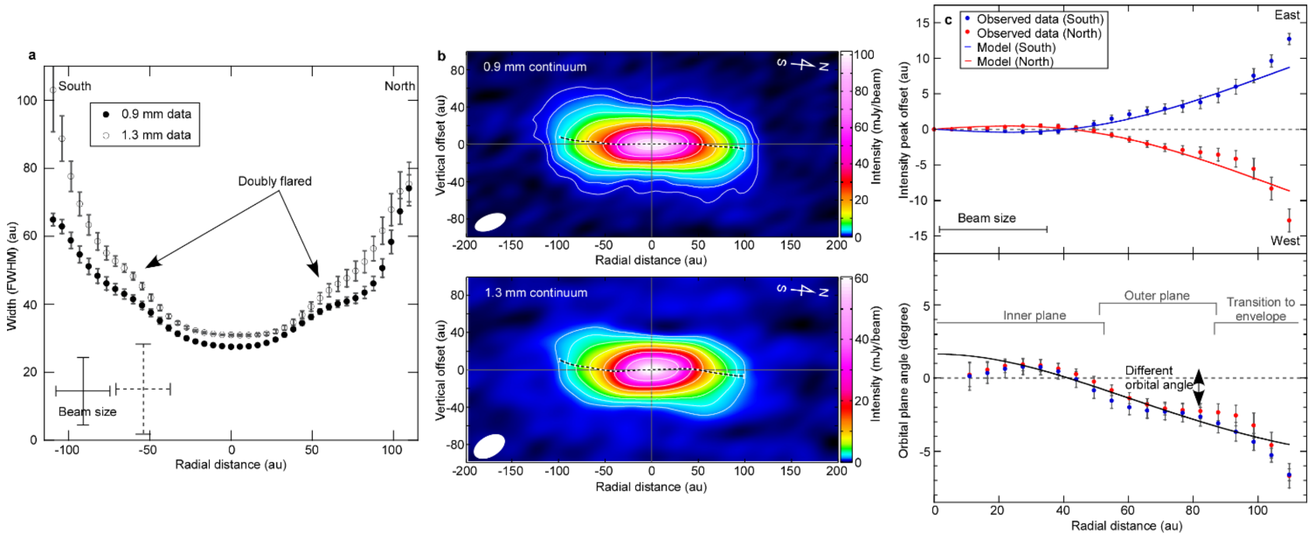


Figure 4 (a)Disk width calculated from a Gaussian fit of the intensity profile at each radius. (b) ALMA views of IRAS 04368+2557 in dust continuum emission. Images at wavelengths of 0.9 mm (top) and 1.3 mm (bottom). (c) Radial dependence of the peak offset from the averaged disk plane in the 0.9mm map. (top) The peak position of the Gaussian fit as a function of the radial distance from the protostar in the map shown in b-top. The southern part and the northern part of the disk are treated separately. (bottom) The vertical offset of the intensity peak at each radial distance is represented in terms of the angle (|θ| < 90°) between the averaged disk-plane and the line connecting the protostar position and the peak position at 0.9 mm.

Highlights of Project C

Before ALMA, we only need to know cold gas phase chemistry and surface chemistry in extremely low temperature and low-density condition. It is different from terrestrial chemistry, and worth studying. However, in the case of the cold interstellar chemistry, we do not need to think about reactions with energy barrier or desorption mechanism of molecules. Following the progress in the last decade, now we really need to know depletion, diffusion, and desorption processes in detail to understand chemical evolution toward proto-planets. There are number of important issues to be studied from the viewpoint of molecular science study. All these processes or values are now very important in astrochemistry. Toward such "collaborative" studies, we are also making an effort for one of those items, that is accurate rest frequencies of molecular lines.

By using ALMA-type receivers, we will observe gas cell instead of the sky. This is an emission-type spectrometer (SUMIRE), and different from conventional type absorption spectrometer. The strong points of this spectrometer are wide frequency coverage. It can be 32 GHz at a time (at most), and reliable intensity. This year, we installed 8 GHz bandwidth backend system. To obtain accurate rest frequency, we installed Rb-GPS clock, which gives 10-12 accuracy. We have succeeded to measure CH_3OH spectrum in 216-264 GHz (ALMA Band 6). The relative intensities of CH_3OH lines are enough reproduced in comparison with the calculated model in CDMS. This is the advantage of this system. Relative intensity of lines is reliable unlike usual absorption type spectrometer. (Watanabe, Tamanai, Sakai et al. in prep.) In astronomical observations, we need accuracy of much less than 0.1 km/s in velocity. That means, 10 kHz or less in this frequency. However, rest frequencies of high excitation lines are significantly shifted from the values in database. This would originate from the effect of higher order perturbation, because most of the values in database are extrapolated ones from the values in lower frequency. It is thus important to measure directly the rest frequencies of molecular lines. We will start full-scale measurement in the next FY.

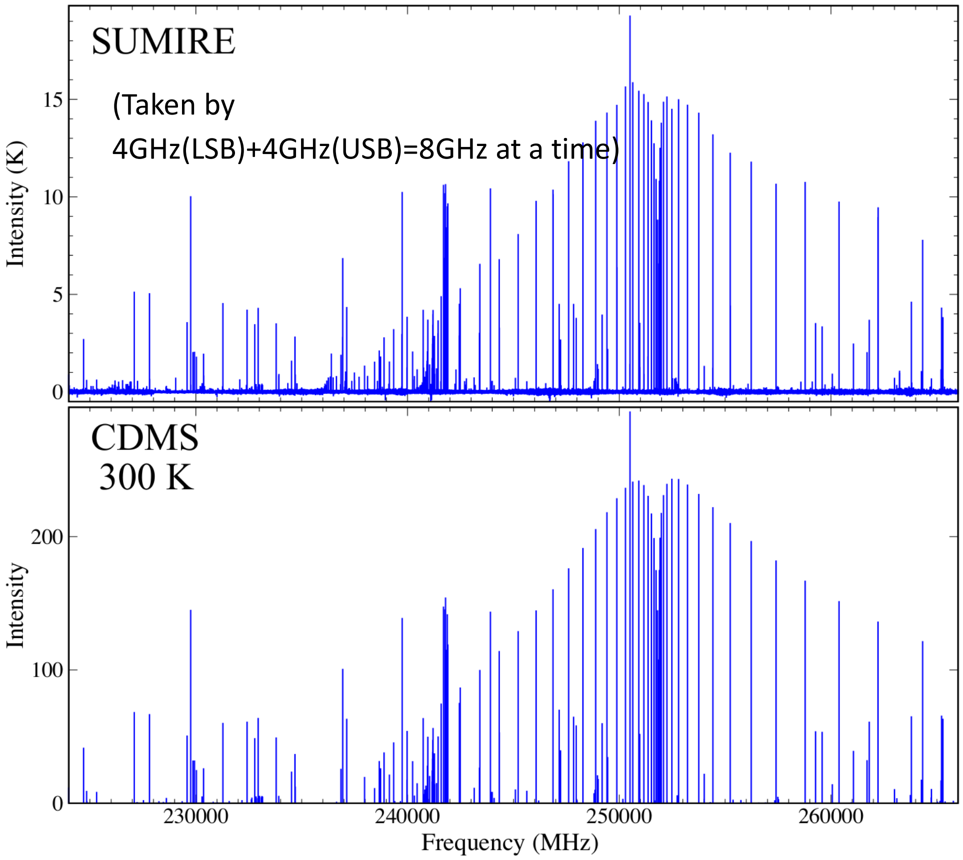


Figure 5 CH_3OH spectrum taken by SUMIRE

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1) Nami Sakai, “Protostellar Disks”, The Early Phase of Star Formation 2018, Munich, Germany, 13-18 May 2018

2) Nami Sakai, “Physics and Chemistry of Disk Formation”, Astrochemistry 2018 Past, Present & Future, CfA (Harvard Smithsonian Center For Astrophysics), Caltech, Pasadena, US, 10-13 Jul. 2018

3) Nami Sakai, “Chemistry during star and planet formation”, NOEMA/30m Workshop, NAOJ, Mitaka, Japan, 24-25 Jul. 2018

4) Hideki Umehata, “ALMA Observations of LABs”, Cosmic Shadow 2018, Ishigaki, Japan, 24 Nov. 2018

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1) Aya Higuchi, Tetsuo Hasegawa, Patricio Sanhueza, Kazuya Saigo, James Chibueze, “ALMA reveals a hub of filamentary molecular clouds in Sgr B2(N)”, Star Formation Triggered by Cloud-Cloud Collision, Nagoya University, Nagoya, Japan, 28 May, 2018

2) Hideki Umehata, “ALMA deep survey in a z=3 proto-cluster field”, IAU General Assembly, Build-up of Galaxy Clusters, IAU, Wien, Austria, 27 Aug. 2018

3) Aya Higuchi, “Gas survey toward debris disks with ALMA”, Japanese-German meeting on Exoplanets and Planet Formation 2018, Edesheim, Germany, 24 Sept. 2018

4) Yichen Zhang, Nami Sakai, Aya Higuchi, Ana López-Sepulcre, Yoko Oya, Muneaki Imai, Takeshi Sakai, Yoshimasa

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5) Satoshi Ohashi, “Different polarization patterns reveal the grain growth, optical depth, and magnetic field in disks”, East Asian ALMA Science Workshop 2018, Osaka Prefecture University, Osaka, Japan, 17-19 Dec. 2018

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1) Nami Sakai, “Astrochemical Approach to Star and Planet Formation”, ISAS Space Science Colloquium & Space Science Seminar, JAXA Sagami Campus, Institute of Space and Astronautical Science, Sagamihara, 23 May, 2018

2) Hideki Umehata, “Dusty star-forming galaxies at a high redshift proto-cluster”, R-Astro-seminar, Wako, Japan, 2 Jul. 2018

3) Hideki Umehata, “Massive Galaxy Formation at a z=3 proto-cluster revealed by ALMA and Subaru”, Subaru Seminar, NAOJ Hawaii Observatory, Hilo, Hawaii, US, 6 Sept. 2018

国内会議・セミナー

1) 樋口あや，佐藤愛樹，塚越崇，百瀬宗武，“Toward understanding origin of gas in debris disks”，日本地球惑星科学連合2018大会，幕張メッセ，2018年5月23日

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2) 坂井南美，国立天文台「ALMA2 Project-アルマ望遠鏡が切り拓く2020年代の科学のフロンティア-」，第三章 3.1.1 太陽系以外の惑星系とその形成 & 第四章 4.1.1 太陽系以外の惑星系とその形成の解明，2019年1月

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Press release

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Award

1) 坂井南美：科学技術への顕著な貢献 2018 (ナイスステップな研究者) 文部科学省 科学技術・学術政策研究所

Acknowledge

1) 科学研究費補助金 [基盤 B] 原始星円盤における化学的多様性の全貌解明と円盤形成過程の探求 2016-2018 (代表：坂井南美)

2) 科学研究費補助金 [基盤 S] 原始惑星系円盤形成領域の化学組成とその進化 2018-2022 (代表：山本智)

3) 科学研究費補助金 [基盤 C] 電波望遠鏡を用いた惑星系形成後期過程の観測的研究 2018-2020 (代表：樋口あや)

4) 科学研究費補助金 [若手研究(B)] 可視面分光とアルマ望遠鏡で探る銀河と銀河間物質の相互作用 2017-2019 (代表：梅畑豪紀)

5) 科学研究費補助金 [若手研究] 分子雲コアから星団形成へ、そして原始星円盤の角運動量の起源を探る 2018-2019 (代表：大橋聡史)

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