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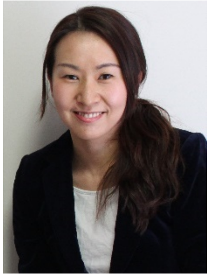


キーセンテンス：
1. 星・惑星系形成過程の研究
2. 星間空間における物質進化の研究
3. 分光実験による分子の回転遷移周波数の精密測定

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

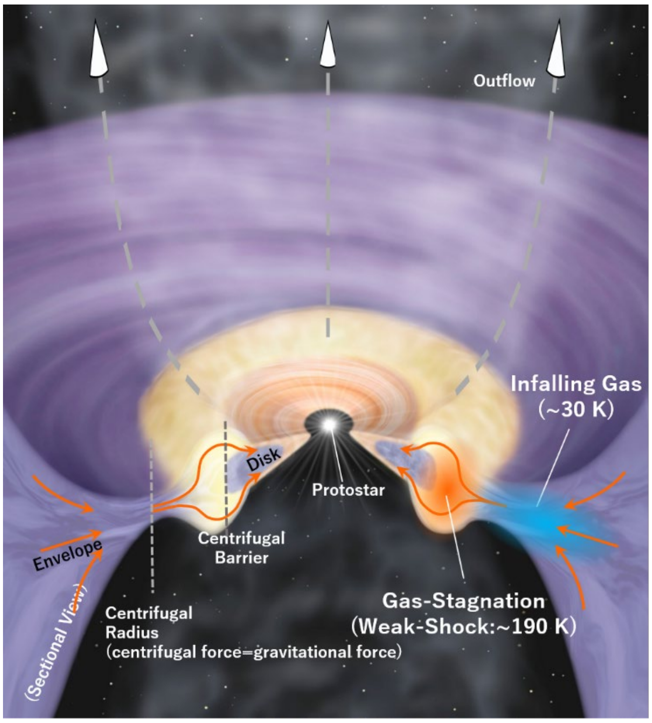
Our body is made up of various elements such as oxygen, carbon, hydrogen, and Nitrogen. Those elements are formed by nucleosynthesis in stars and scattered across the Universe and are building blocks of life. Among all the elements, carbon is very special element. It has four bonding sites for other atoms, and is the key atom to make variety of organic molecules. Thus, understanding molecular formation, especially carbon-bearing species, along star and planet formation is evenually related to know the origin of our existence.

A new star is formed by gravitational contraction of an interstellar molecular cloud consisting of gas and dust. In the course of this process, a gas disk (protostellar/protoplanetary disk) is formed around the protostar, and is evolved into a planetary system. The Solar system was also formed in this way about 4.6 billion years ago, and the life eventually emerged in the Earth. How is the situation happened for the Solar system unique in the Universe? In order to answer this question, **understanding formation of protoplanetary disks and associated chemical evolution in various star-forming regions** is essential, and various observational efforts have been done toward this goal. Increasing sensitivity of various telescopes allows us to identify 196 interstellar molecules so far, about 1/3 of which are "complex" molecules having 6 atoms or more. This indicates the high chemical complexity of interstellar clouds even in the extreme condition, which would ultimately be related to the origin of rich substances in the Solar System.

In the last two decades, it is clearly demonstrated that gas surrounding solar-type protostars have significant chemical diversity: some sources harbor various saturated- "complex-" organic molecules (COMs) such as $HCOOCH_3$, $(CH_3)_2O$, and C_2H_5CN, whereas some others harbor highly-unsaturated species instead. The chemical diversity would originate from different duration time of the starless cloud phase of each protostar. On the other hand, the most interesting issue to be studied is how the chemical diversity in the protostellar envelopes is brought into the later stages toward protoplanetary disks. Fortunately, such studies are now feasible with high sensitivity and angular-resolution capabilities of ALMA (Atacama Large Millimeter/Submillimeter Array). At the same time, to reveal whole view of chemical diversity in the Universe, we also have to investigate chemical complexity of the molecular cloud cores, formation mechanism of COMs in those cloud, and chemical composition of interstellar cloud even in other galaxies.

This FY, we have carried out the following studies. (1) Revealing vertical structure of disk forming region, (2)the 2nd and 3rd cases of disk harboring hot corino chemistry, (3) a chemically hybrid-type disk, (4)origin of COMs in starless cores, (5) whole chemical views of giant molecular clouds, and (6) development of spectrometer and test measurement. Highlights of our results are presented.

1. Revealing vertical structure of disk forming region



We have resolved for the first time radial and vertical structures of the almost edge-on envelope/disk system of the low-mass Class 0 protostar L1527 at a resolution of 0.1”-0.3” (15-30 au) for 0.8 mm band with ALMA. While a thin infalling-rotating envelope (~50 au) is seen in the CCH emission outward of about 150 au, its thickness is increased by a factor of 2 inward of it. The transition is located between the centrifugal radius (200 au) and the centrifugal barrier (100 au) of the infalling-rotating envelope. It seems that the gas is stagnated in front of the centrifugal barrier and moving along the direction vertical to the mid-plane. The SO emission is concentrated around and inside the centrifugal barrier. The rotation motion of the gas containing SO is found to be decelerated around the centrifugal barrier. A part of the angular momentum could be extracted by the gas moving away from the mid-plane around the centrifugal barrier. If it is the case, the centrifugal barrier may be related to launching mechanisms of disk winds or outflows. (Ref. paper 4)

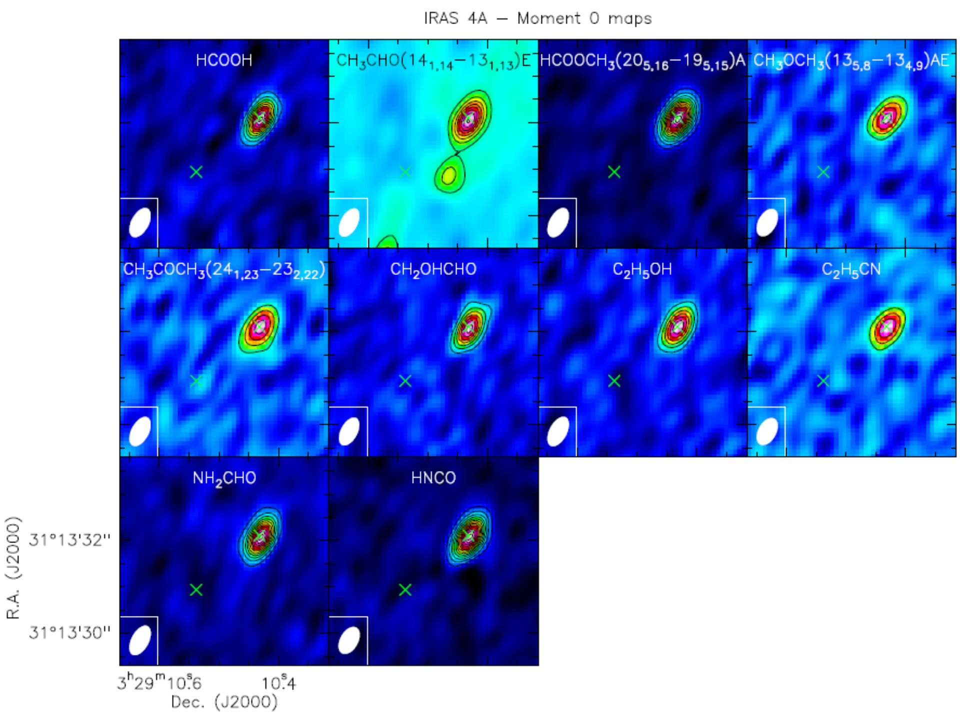
2&3. The 2nd and 3rd cases of disk harboring hot corino chemistry and a chemically hybrid-type disk

From the chemical point of view, envelopes of solar-type protostars seem to be classified into two classes: hot corinos and WCCC (Warm Carbon-Chain Chemistry) sources. The former is characterized by abundant COMs (Saturated-Complex Organic Molecules), whereas the latter is characterized by rich unsaturated-organic (carbon-chain) molecules. We recently studied sub-arcsecond molecular distributions in the prototypical WCCC source L1527 and the prototypical hot corino source IRAS16293-2422A with ALMA, and found that the chemical diversity is also evident in the closest vicinity around the protostar. Thus, understanding the chemical diversity in disk forming regions becomes more and more important in understanding the "chemical" origin of the Solar System. Moreover, the ALMA observations revealed the presence of a centrifugal barrier, which represents the transition between the infalling-rotating envelope and the rotationally supported disk. In WCCC sources, the infalling-rotating envelope is traced by carbon-chain molecules and CS, while SO traces the centrifugal barrier. In hot corinos, the infalling-rotating envelope is traced by CS and OCS, while the centrifugal barrier would be traced by COMs. Although species tracing each part are different, the centrifugal barrier is identified in the both types of sources.

Next questions are “Are L1527 and IRAS16293-2422 special cases or representative sources?” and “Are there any source rich in both of saturated COMs and unsaturated COMs?” To answer these questions, we have conducted observations toward L483 (young protostellar object:YSO in Aquila Lift), NGC1333IRAS4A (YSO in Perseus), and IRAS16293-2422B (YSO, binary counterpart of IRAS16293-2422A, in Ophiucus).

2-1.Hybrid Source: The infalling–rotating envelope of L483, a Class0 protostar, is traced by the CS line, while a very compact component with a broad velocity width is observed for the CS, SO, HNCO, NH2CHO, and $HCOOCH_3$ lines. Although this source is regarded as the warm carbon-chain chemistry (WCCC) candidate source at a 1000 au scale, complex organic molecules characteristic of hot corinos such as NH_2CHO and $HCOOCH_3$ are detected in the vicinity of the protostar. Thus, both hot corino chemistry and WCCC are seen in L483. Although such a mixed chemical character source has been recognized as an intermediate source in previous single-dish observations, we here report the first spatially resolved detection.　A kinematic structure of the infalling-rotating envelope is roughly explained by a simple ballistic model with a protostellar mass of 0.1–0.2 M. and a radius of the centrifugal barrier (half of the centrifugal radius) of 30–200 au, assuming an inclination angle of 80° (0° for face-on). The broad-line emission observed in the above molecules most likely comes from the disk component inside the centrifugal barrier. Thus, a drastic chemical change is seen around the centrifugal barrier. Important point of this result is, there could be hybrid source, which harbors both hot corino and WCCC characteristics.　The hot corino sources and WCCC sources could be two extreme cases. We need statistical study to reveal the fraction of each chemical category, and the origin of their differences to understand whole picture of chemical evolution. (Ref. paper 3)

2-2. Diversity? or High Dust-Opacity?:　The infalling-rotating envelopes/disks of the binary protostar, NGC1333 IRAS 4A1/A2 are investigated by ALMA with angular resolution of 0.5”. Kinematically, we could not identify the centrifugal barrier (i.e. disk edge).　On the other hand, we revealed that COMs are extremely abundant in the disk forming region of source A2.　Molecular emission from organic molecules is concentrated exclusively in A2, while A1 appears completely devoid of COMs or even simpler organic molecules such as HNCO despite it being the strongest continuum emitter. A2 displays typical hot corino abundances, which are higher than reported in previous lower-resolution studies by an order of magnitude. The hot corino has a deconvolved size of 70 au.　In contrast, the upper limits we placed on COMs abundances for A1 are extremely low, surprisingly lying about one order of magnitude below pre-stellar values. The appearance of the amount of COMs present in A1 and A2 is huge, ranging



between a factor ~ 20 and ~ 300. It is not clear that this significant difference is originate from chemical diversity or from high dust-opacity in A1 disk. However, at least A2 shows the second hot corino disk example. (Ref. paper 11)
Figure 2. The Northwest source (A2) is abundant in various COMs whereas not in A2(Southeast). (Ref. paper 11)

2-3 Geometrically Thick Disk: We have analyzed the OCS, H_2CS, CH_3OH, and $HCOOCH_3$ data observed toward the low-mass protostar IRAS 16293–2422 Source B at a sub-arcsecond resolution with ALMA. A clear chemical differentiation is seen in their distributions; OCS and H_2CS are extended with a slight rotation signature, while CH_3OH and $HCOOCH_3$ are concentrated near the protostar. Such a chemical change in the vicinity of the protostar is similar to the companion (Source A) case. The extended component is interpreted by the infalling-rotating envelope model with a nearly face-on configuration. The radius of the centrifugal barrier of the infalling-rotating envelope is roughly evaluated to be (30–50) au. The observed lines show the inverse P-Cygni profile, indicating the infall motion within a few 10 au from the protostar. The nearly pole-on geometry of the outflow lobes is inferred from the SiO distribution, and thus, the infalling and outflowing motions should coexist along the line of sight to the protostar. This implies that the infalling gas is localized near the protostar and the current launching points of the outflow have an offset from the protostar. Geometrically thick disk, which is going to be settle down to thinner disk with hydrostatic equilibrium, is the most expected reason to have such kinematical features. From the chemical point of view, this is the 3rd case of hot corino type disk ever found. (Ref. Paper 19)

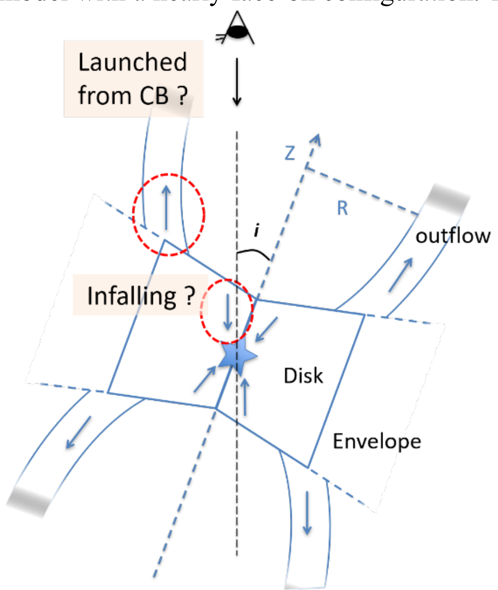
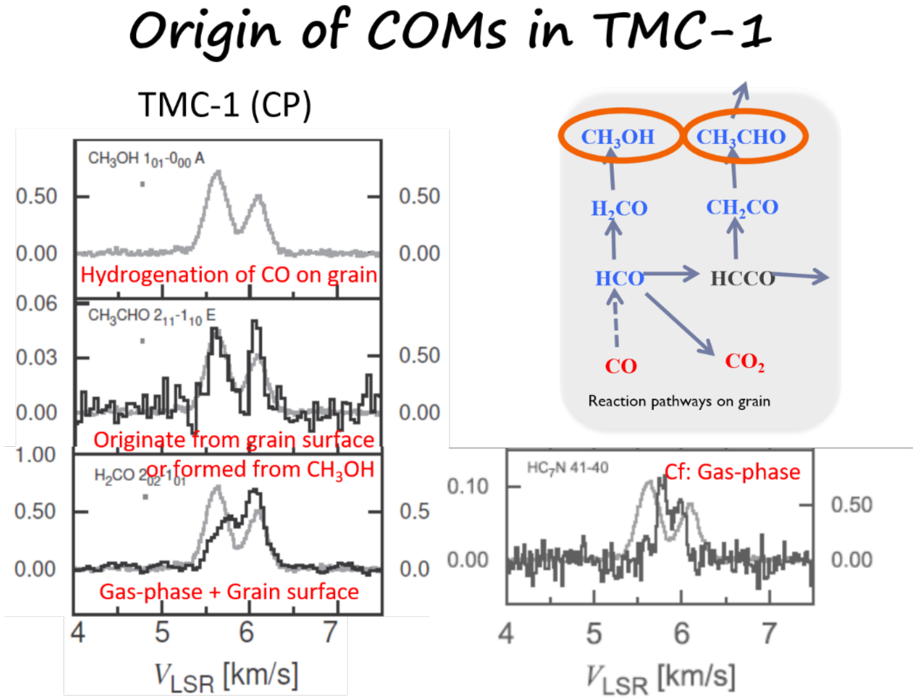


Figure 3. Expected structure of the forming disk around IRAS16293-2422B (copyright: Y.Oya).

4. Origin of COMs in starless cores

We have observed the millimeter-wave rotational spectral lines of CH_3CHO, H_2CCO, cyclopropenone, and H_2CO toward the cyanoployyne peak of Taurus Molecular Cloud-1 (TMC-1 CP). The spectral line profile of CH_3CHO is found to reveal a well-separated double peak. It is similar to the line profile of CH_3OH, but is much different from those of carbon-chain molecules and C34S. The different line profiles mean different distributions along the line of sight. The similarity of the spectral line profiles between CH_3CHO and CH_3OH suggests that CH_3CHO is mainly formed on dust grains as CH_3OH or through gas-phase reactions starting from CH_3OH. On the other hand, the spectral line profiles of H_2CCO and cyclopropenone are rather similar to those of carbon-chain molecules and $C^{34}S$, implying their gas-phase productions. H_2CO shows a composite spectral line profile reflecting the contributions of both gas-phase and grain-surface productions. In addition, we have detected the spectral lines of CH_3CHO and $HCOOCH_3$ toward the methanol peak near TMC-1 CP. We have also tentatively detected one line of $(CH_3)_2O$. Considering the chemical youth of TMC-1, the present results indicate that fairly complex organic species have already been formed in the early evolutionary phase of starless cores. TMC-1 is thus recognized as a novel source where formation processes of complex organic molecules can be studied on the basis of the line profiles. (Ref. Paper 20)



5. Whole chemical views of giant molecular clouds

We have conducted a mapping spectral line survey toward the Galactic giant molecular cloud W51 in the 3 mm band with the Mopra 22m telescope in order to study an averaged chemical composition of the gas extended over a molecular-cloud scale in our Galaxy. We have observed the area of 25′×30′, which corresponds to 39pc×47pc. The frequency ranges of the observation are 85.1–101.1GHz and 107.0–114.9GHz. In the spectrum spatially averaged over the observed area, spectral lines of 12 molecular species and 4 additional isotopologues are identified. An intensity pattern of the spatially averaged spectrum is found to be similar to that of the spiral arm in the external galaxy M51, indicating that these two sources have similar chemical compositions. The observed area has been classified into five subregions according to the integrated intensity of $^{13}CO(J=1\text{-}0)$ (I_{13CO}), and contributions of the fluxes of 11 molecular lines from each subregion to the averaged spectrum have been evaluated. For most of the molecular species, 50% or more of the flux comes from the subregions with I_{13CO} from 25 to 100Kkms−1, which does not involve active star-forming regions. Therefore, the molecular-cloud scale spectrum observed in the 3 mm band hardly represents the chemical composition of star-forming cores, but mainly represents the chemical composition of an extended quiescent molecular gas.

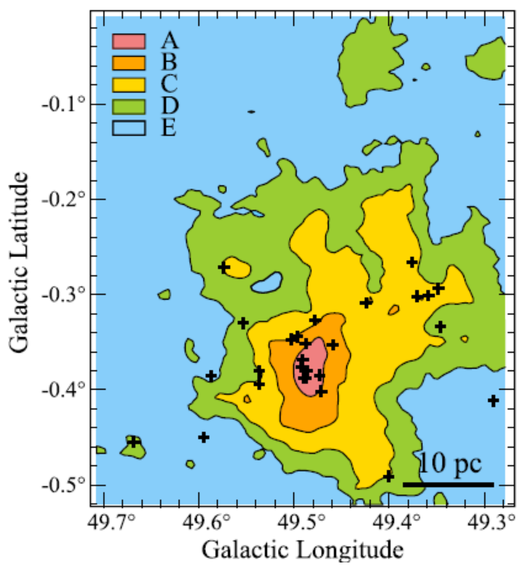


Fig.5 Definitions of subregions A to E, categorized by I_{13CO} in W51 region.

The present result constitutes a sound base for interpreting the spectra of external galaxies at a resolution of a molecular-cloud scale (~10pc) or larger. Similar results are also reported toward W3(OH) region. (Ref. Paper 7& 13)

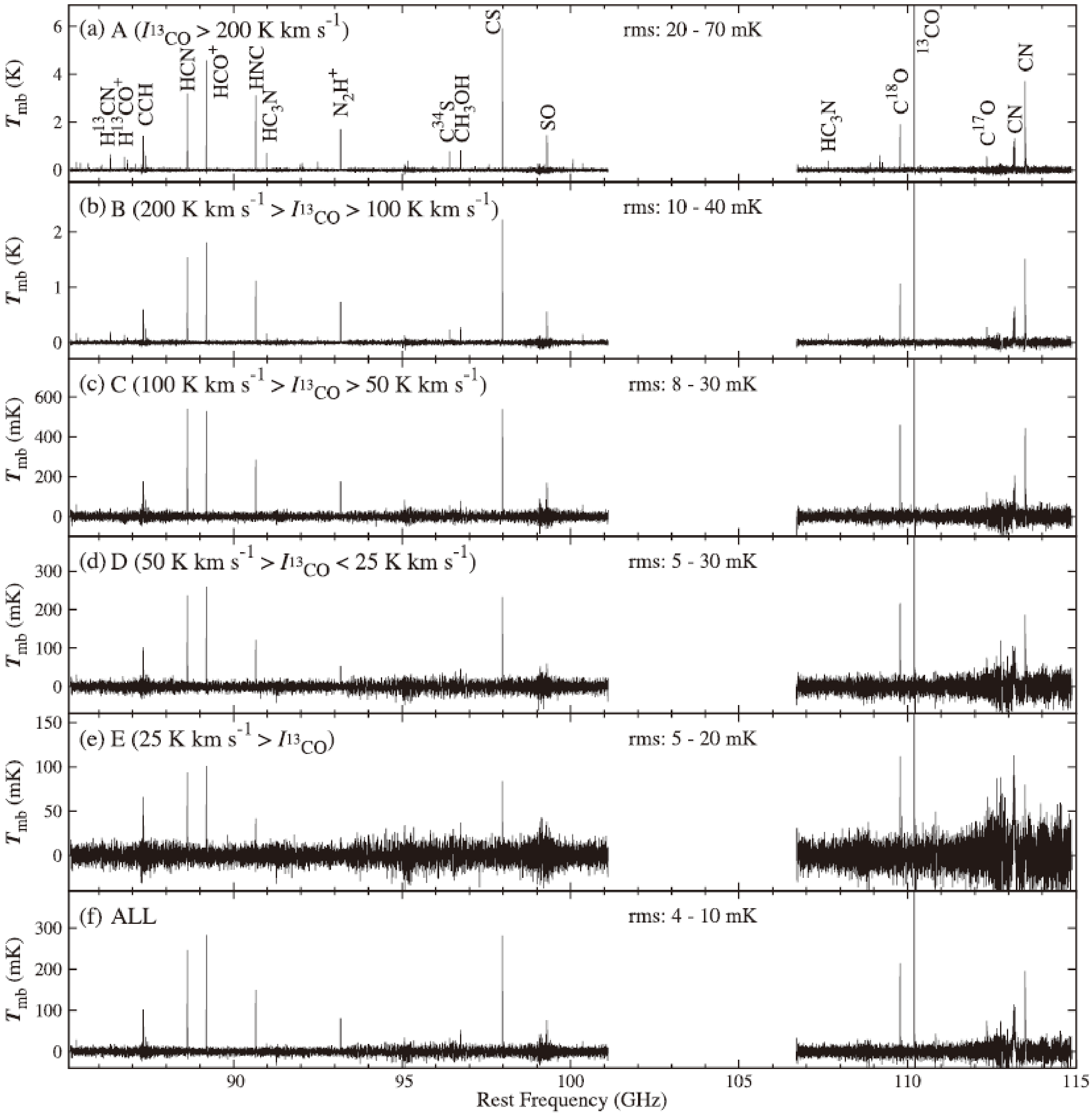
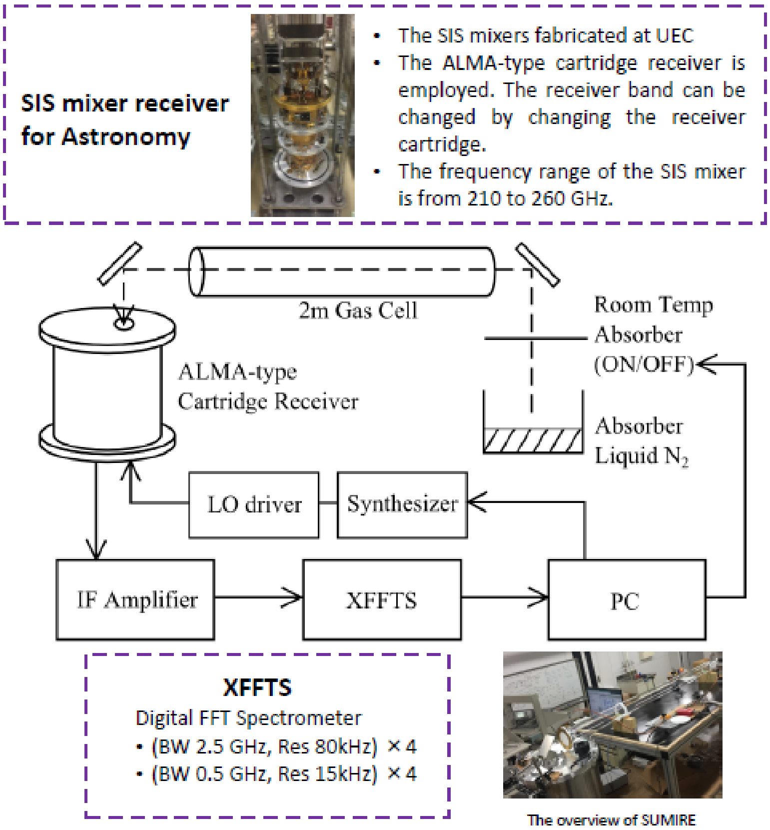


Fig.6 Mapping line survey results toward W51 star forming region in our Galaxy.

6. Development of spectrometer (SUMIRE)

In radio astronomy, accurate rest frequencies of molecular transitions are indispensable for secure identification of molecular species and accurate analyses of Doppler shifts caused by motions of the target sources. Rest frequencies of various molecules have been measured in the laboratory, but their accuracies are sometimes insufficient for the above astronomical purposes. With this in mind, we are developing a new emission spectrometer called SUMIRE

(Spectrometer Using superconductor MIxer REceiver) at RIKEN. This spectrometer is equipped with an ALMA-type 230 GHz SIS mixer receiver and XFFTS spectrometer with the spectral resolution of a few tens of kHz as a back end.



We have successfully launched SUMIRE this year. Test measurements of HDO, D2O, and CH_3OH are conducted. The line shape (HDO 225.89672 GHz) gradually changes from Gaussian to Lorentzian as the pressure increases. Doppler broadening seems to be dominant at low pressure. We could find significant shift of the rest frequencies of HDO from those in database. The origin of the shift will be investigated by introducing accurate clock (10^{-11} or more) to the signal generator. Furthermore, the frequency range of this spectrometer will be extended to terahertz frequencies by using the hot electron bolometer (HEB) mixer receiver.

Fig. 7 Setups of SUMIRE.

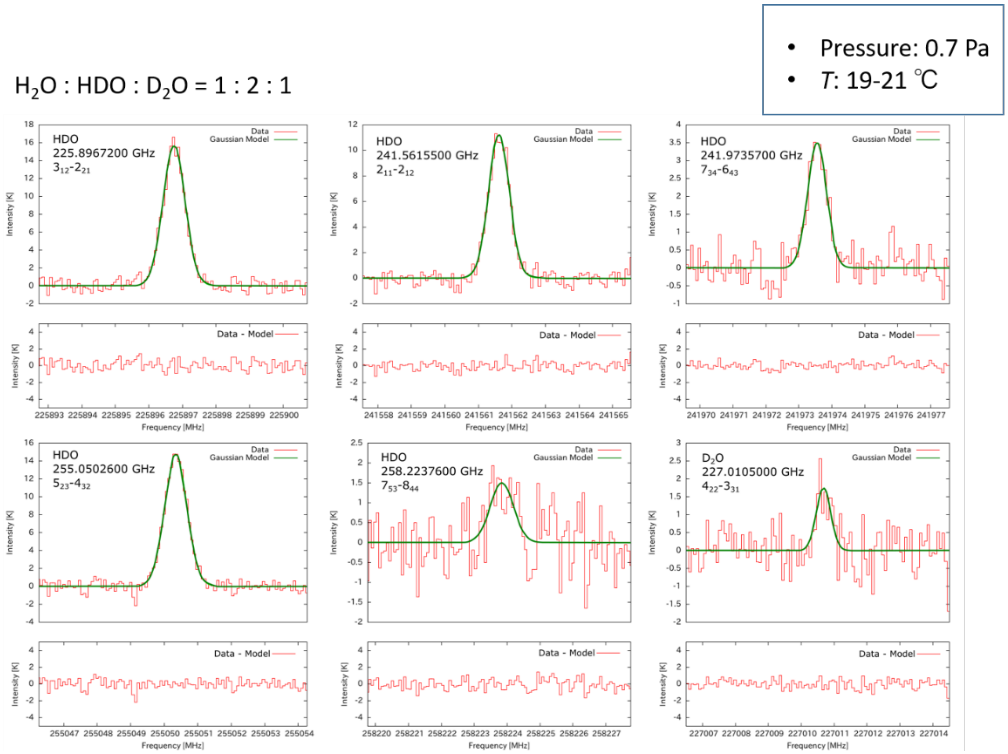


Fig. 8 Test spectrum of HDO taken by SUMIRE.

Publications (Refereed papers)

1) Aya E. Higuchi, Aki Sato, Takashi Tsukagoshi, Nami Sakai, Kazunari Iwasaki, Munetake Momose, Hiroshi Kobayashi, Daisuke Ishihara, Sakae Watanabe, Hidehiro Kaneda and Satoshi Yamamoto, "Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris", Astrophys. J. Lett., 839, L14 (6 pp), Apr. 2017

2) James O. Chibueze, Timea Csengeri, Ken'ichi Tatematsu, Tetsuo Hasegawa, Satoru Iguchi, Jibrin A. Alhassan, Aya E. Higuchi, Sylvain Bontemps, and Karl M. Menten, "Class II 6.7 GHz Methanol Maser Association with Young Massive Cores Revealed by ALMA", Astrophys. J., **2017**, 836, 59 (8 pages).

3) Yoko Oya, Nami Sakai, Yoshimasa Watanabe, Aya E. Higuchi, Tomoya Hirota, Ana Lopez-Sepulcre, Takeshi Sakai, Yuri Aikawa, Cecilia Ceccarelli, Bertrand Lefloch, Emmanuel Caux, Charlotte Vastel, Claudine, Kahane, and Satoshi Yamamoto, "L483: Warm Carbon-Chain Chemistry Source Harboring Hot Corino Activity", Astrophys. J., **2017**, 837, 174.

4) Nami Sakai, Yoko Oya, Aya E. Higuchi, Yuri Aikawa, Tomoyuki Hanawa, Cecillia Ceccarelli, Bertrand Lefloch, Ana Lopez-Sepulcre, Yoshimasa Watanabe, Takeshi Sakai, Tomoya Hirota, Emmanuel Caux, Charlotte Vastel, Claudine Kahane, Satoshi Yamamoto, "Vertical Structure of the Transition Zone from Infalling Rotating Envelope to Disk in the Class 0 Protostar, IRAS04368+2557", Mon Not R Astron Soc., 467, L76-L80, May 2017

5) James M. De Buizer, Mengyao Liu, Jonathan C. Tan, Yichen Zhang, Maria T. Beltrán, Ralph Shuping, Jan E. Staff, Kei E. I. Tanaka and Barbara Whitney, "The SOFIA Massive (SOMA) Star Formation Survey. I. Overview and First Results", Astrophys. J., 843, 33 (27 pp), Jul. 2017

6) Junko Ueda, Yoshimasa Watanabe, Daisuke Iono, David J. Wilner, Giovanni G. Fazio, Satoshi Ohashi, Ryohei Kawabe, Toshiki Saito, Shinya Komugi, "ALMA observations of the dense and shocked gas in the nuclear region of NGC 4038 (Antennae galaxies)", Publ. Astron. Soc. Japan, **2017**, 69, 6 (9 pages)

7) Yoshimasa Watanabe, Yuri Nishimura, Nanase Harada, Nami Sakai, Takashi Shimonishi, Yuri Aikawa, Akiko Kawamura and Satoshi Yamamoto, "Molecular-cloud-scale Chemical Composition. I. A Mapping Spectral Line Survey toward W51 in the 3 mm Band", Astrophys. J., 845, 116 (30 pp), Aug. 2017

8) F. Fontani, C. Ceccarelli, C. Favre, P. Caselli, R. Neri, I. R. Sims, C. Kahane, F. O. Alves, N. Balucani, E. Bianchi, E. Caux, A. Jaber AI-Edhari, A. Lopez-Sepulcre, J. E. Pineda, R. Bachiller, L. Bizzocchi, S. Bottinelli, A. Chacon-Tanarro, R. Choudhury, C. Codella, A. Coutens, F. Dulieu, S. Feng, A. Rimola, P. Hily-Blant, J. Holdship, I. Jimenez-Serra, J. Laas, B. Lefloch, Y. Oya, L. Podio, A. Pon, A. Punanova, D. Quenard, N. Sakai, S. Spezzano, V. Taquet, L Testi, P. Theule, P. Ugliengo, C. Vastel, A. I. Vasyunin, S. Viti, S. Yamamoto and L. Wiesenfeld, "Seeds of Life in Space (SOLIS). I. Carbon-chain growth in the Solar-type protocluster OMC2-FIR4", Astron. Astrophys. 605, A57 (11 pp), Sept. 2017

9) C. Codella, C. Ceccarelli, P. Caselli, N. Balucani, V. Barone, F. Fontani, B. Lefloch, S. Viti, S, Feng, R. Bachiller, E. Bianchi, F. Dulieu, I. Jimenez-Serra, J. Holdship, R. Neri, J. E. Pineda, A. Pon, I Sims, S. Spezzano. A. I. Vasyunin, F. Alves, L. Bizzocchi, S. Bottinelli, E. Caux, A. Chacon-Tanarro, R. Choudhury, A. Coutens, C. Favre, P. Hily-Blant, C. Kahane, A. Jaber AI-Edhari, J. Laas, A. Lopez-Sepulcre, J. Ospina, Y. Oya, A. Punanova, C. Puzzarini, D. Quenard, A. Rimola, N. Sakai, D. Skouteris, V. Taquet, L. Testi, P. Theule, P. Ugliengo, C. Vastel, F. Vazart, L. Wiesenfeld and

S. Yamamoto, “Seeds of Life in Space (SOLIS). II. Formamide in protostellar shocks: Evidence for gas-phase formation”, Astron. Astrophys. 605, L3 (7 pp), Sept. 2017

10) Mitsunori Araki, Shuro Takano, Nami Sakai, Satoshi Yamamoto, Takahiro Oyama, Nobuhiko Kuze and Koichi Tsukiyama “Long Carbon Chains in the Warm Carbon-chain-chemistry Source L1527: First Detection of C7H in Molecular Clouds”, Astrophys.J., 847, 51 (7 pp), Sept.2017

11) A. López-Sepulcre, N. Sakai, R. Neri, M. Imai, Y. Oya, C. Ceccarelli, A. E. Higuchi, Y. Aikawa, S. Bottinelli, E. Caux, T. Hirota, C. Kahane, B. Lefloch, C.Vastel, Y. Watanabe and S. Yamamoto, “Complex organics in IRAS 4A revisited with ALMA and PdBI: Striking contrast between two neighboring protostellar cores”, Astron. Astrophys. 606, A121 (12 pp), Oct. 2017

12) Yoshimasa Watanabe, Nami Sakai, Ana López-Sepulcre, Takeshi Sakai, Tomoya Hirota, Sheng-Yuan Liu, Yu-Nung Su and Satoshi Yamamoto, “Discovery of Striking Difference of Molecular-emission-line Richness in the Potential Proto-binary System NGC 2264 CMM3”, Astrophys. J., 847, 108 (8 pp), Oct. 2017

13) Yuri Nishimura, Yoshimasa Watanabe, Nanase Harada, Takashi Shimonishi, Nami Sakai, Yuri Aikawa, Akiko Kawamura and Satoshi Yamamoto, “Molecular-cloud-scale Chemical Composition. II. Mapping Spectral Line Survey toward W3(OH) in the 3 mm Band”, Astrophys. J., 848, 17 (18 pp), Oct. 2017

14) Tomofumi Umemoto, Tetsuhiro Minamidani, Nario Kuno, Shinji Fujita, Mitsuhiro Matsuo, Atsushi Nishimura, Kazufumi Torii, Tomoka Tosaki, Mikito Kohno, Mika Kuriki, Yuya Tsuda, Akihiko Hirota, Satoshi Ohashi, Mitsuyoshi Yamagishi, Toshihiro Handa, Hiroyuki Nakanishi, Toshihiro Omodaka, Nagito Koide, Naoko Matsumoto, Toshikazu Onishi, Kazuki Tokuda, Masumichi Seta, Yukinori Kobayashi, Kengo Tachihara, Hidetoshi Sano, Yusuke Hattori, Sachiko Onodera, Yumiko Oasa,Kazuhisa Kamegai, Masato Tsuboi, Yoshiaki Sofue, Aya E. Higuchi, James O Chibueze, Norikazu Mizuno, Mareki Honma, Erik Muller, Tsuyoshi Inoue, Kana Morokuma-Matsui Hiroko Shinnaga, Takeaki Ozawa, Ryo Takahashi, Satoshi Yoshiike, Jean Costes and Sho Kuwahara, “FOREST unbiased Galactic plane imaging survey with the Nobeyama 45 m telescope (FUGIN). I. Project overview and initial results”, PASJ, 69, 78, Oct. 2017

15) Minho Choi, Miju Kang, Jeong-Eun Lee, Ken'ichi Tatematsu, Sung-Ju Kang, Jack Sayers, Neal J. Evans II, Jungyeon Cho, Jungmi Kwon, Geumsook Park, Satoshi Ohashi, Hyunju Yoo and Youngung Lee, “Precessing Jet and Large Dust Grains in the V380 Ori NE Star-forming Region”, Astrophys. J., Suppl. Ser., 232, 24 (19 pp), Oct. 2017

16) Kei E. I. Tanaka, Jonathan C. Tan, Jan E. Staff and Yichen Zhang, “Outflow-confined H II Regions. II. The Early Break-out Phase”, Astrophys. J., 849, 133 (9 pp), Nov. 2017

17) C. Ceccarelli, P. Caselli, F. Fontani, R. Neri, A. López-Sepulcre, C. Codella, S. Feng, I. Jiménez-Serra, B. Lefloch, J. E. Pineda, C. Vastel, F. Alves, R. Bachiller, N. Balucani, E. Bianchi, L. Bizzocchi, S. Bottinelli, E. Caux, A. Chacón-Tanarro, R. Choudhury, A. Coutens, F. Dulieu, C. Favre, P. Hily-Blant, J. Holdship, C. Kahane, A. Jaber Al-Edhari, J. Laas, J. Ospina, Y. Oya, L. Podio, A. Pon, A. Punanova, D. Quenard, A. Rimola, N. Sakai, I. R. Sims, S. Spezzano, V. Taquet, L. Testi, P. Theulé, P. Ugliengo, A. I. Vasyunin, S. Viti, L. Wiesenfeld, and S. Yamamoto, “Seeds Of Life In Space (SOLIS): The Organic Composition Diversity at 300-1000 au Scale in Solar-type Star-forming Regions”, Astrophys. J., 850, 176 (15 pp), Dec. 2017

18) Yichen Zhang and Jonathan C. Tan, “Radiation Transfer of Models of Massive Star Formation. IV. The Model Grid and Spectral Energy Distribution Fitting”, Astrophys. J., 853, 18 (24 pp), Jan. 2018

19) Yoko Oya, Kana Moriwaki, Shusuke Onishi, Nami Sakai, Ana López–Sepulcre, Cécile Favre, Yoshimasa Watanabe, Cecilia Ceccarelli, Bertrand Lefloch and Satoshi Yamamoto, “Chemical and Physical Picture of IRAS 16293-2422 Source B at a Sub-arcsecond Scale Studied with ALMA”, Astrophys. J., 854, 96 (19 pp), Feb. 2018

20) Tatsuya Soma, Nami Sakai*, Yoshimasa Watanabe and Satoshi Yamamoto, “Complex Organic Molecules in Taurus Molecular Cloud-1”, Astrophys. J., 854, 116 (11 pp), Feb. 2018

21) Anna Punanova, Paola Caselli, Siyi Feng, Ana Chacón-Tanarro, Cecilia Ceccarelli, Roberto Neri, Francesco Fontani, Izaskun Jiménez-Serra, Charlotte Vastel, Luca Bizzocchi, Andy Pon, Anton I. Vasyunin, Silvia Spezzano, Pierre Hily-Blant, Leonardo Testi, Serena Viti, Satoshi Yamamoto, Felipe Alves, Rafael Bachiller, Nadia Balucani, Eleonora Bianchi, Sandrine Bottinelli, Emmanuel Caux, Rumpa Choudhury, Claudio Codella, François Dulieu, Cécile Favre, Jonathan Holdship, Ali Jaber Al-Edhari, Claudine Kahane, Jake Laas, Bertrand LeFloch, Ana López-Sepulcre, Juan Ospina-Zamudio, Yoko Oya, Jaime E. Pineda, Linda Podio, Davide Quenard, Albert Rimola, Nami Sakai, Ian R. Sims, Vianney Taquet, Patrice Theulé and Piero Ugliengo, “Seeds of Life in Space (SOLIS). III. Zooming Into the Methanol Peak of the Prestellar Core L1544”, Astrophys. J., 855, 112 (13 pp), Mar. 2018

International Conference

Oral Presentation (Invited)

1) Nami Sakai, “Chemical Diversity in Protostellar Disks and Its Future”, Gordon Research Conference (GRC) on Origins of Solar Systems: Making a Habitable Planet, Mount Holyoke College, South Hadley, MA, USA, 18-23 Jun. 2017

2) Nami Sakai, “Barriers (centrifugal) in disk formation and chemical signatures”, Disk Formation Workshop 2017, Leiden, Netherlands, 24-27 Jul. 2017

3) Aya Higuchi, Nami Sakai, Aki Sato, Takeshi Tsukagoshi, Munetake Momose, Kazunari Iwasaki, Hiroshi Kobayashi, Daisuke Ishihara, Hidehiro Kanda, “Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris”, NRO45m/ASTE Single Dish Science Workshop 2017, NAOJ Nobeyama Radio Observatory, Japan, 1-2 Aug. 2017

4) Nami Sakai, “Tracing chemistry toward protoplanetary disks by ALMA”, The XXIV International Symposium of Free Radicals (ISFR2017), The International Free Radicals Symposium Committee, Hayama, Japan, 27 Aug. – 1 Sept. 2017

5) Nami Sakai, Yoko Oya, Muneaki Imai, Satoshi Yamamoto, Yichen Zhang, Aya Higuchi, Cecilia Ceccarelli, Bertrand Lefloch, Charlotte Vastel, Ana Lopez-Sepulcre, Tomoyuki Hanawa, Yuri Aikawa, Takeshi Sakai, Tomoya Hirota, “Disk Formation: Observational Challenge”, ALMA Long Baseline Workshop, Mielparque Kyoto, Japan, 3-5 Oct. 2017

6) Aya Higuchi, Nami Sakai, Ana Lopez-Sepulcre, Yoko Oya, Muneaki Imai, Kento Yoshida, Yoshimasa Watanabe, Yichen Zhang, Takeshi Sakai, Tomoya Hirota, Satoshi Yamamoto, “Unbiased Chemical Survey of Protostellar Sources in Perseus”, ALMA Workshop 2017, Star Formation with ALMA: Evolution from dense cores to protostar, NAOJ, Mitaka, Japan, 26 Oct. 2017

7) Aya Higuchi, Nami Sakai, Aki Sato, Takeshi Tsukagoshi, Munetake Momose, Kazunari Iwasaki, Hiroshi Kobayashi, Daisuke Ishihara, Hidehiro Kaneda and Satoshi Yamamoto, “Detection of Submillimeter-wave [C I]

Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris", 10th RESCEU/Planet2 Symposium, Planet Formation around Snowline, University of Tokyo, Japan, 28-30 Nov. 2017

8) Nami Sakai, "Chemical History of Young Sun-like Stars: Why are we here?", International Symposium on the Development of Life -Unfolding with interdisciplinary views-, University of Miyazaki, Japan, 11, Dec. 2017

9) Aya Higuchi, Nami Sakai, Aki Sato, Takeshi Tsukagoshi, Munetake Momose, Kazunari Iwasaki, Hiroshi Kobayashi, Daisuke Ishihara, Hidehiro Kaneda and Satoshi Yamamoto, "Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris", ALMA /45m/ASTE Users Meeting 2017, NAOJ, Mitaka, Japan, 26-27 Dec. 2017

Contributed (International)

1) Aya Higuchi, Nami Sakai, Aki Sato, Takeshi Tsukagoshi, Munetake Momose, Kazunari Iwasaki, Hiroshi Kobayashi, Daisuke Ishihara, Hidehiro Kaneda and Satoshi Yamamoto, "Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris", Workshop on Gaseous Debris Workshop, Wako, Saitama, Japan, 10 Oct. 2017

2) Nami Sakai, "Disk properties in a Class 0 protostar", Workshop on gaseous debris disks, Wako, Saitama, Japan, 11 Oct. 2017

Domestic Conference

1) 坂井南美, "科学で探る円盤形成", 地球惑星連合大会, アルマによる惑星科学の新展開, 幕張メッセ, 千葉, 2017 年 5 月 24 日

2) 坂井南美, 花輪知幸, Yichen Zhang, 樋口あや, 大屋瑶子, 山本智, "Disk Structure around the Class 0 Protostar in L1527", P107a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

3) 樋口あや, 坂井南美, 大屋瑶子, 今井宗明, 山本智, 渡邊祥正, Ana Lopez-Sepulcre, 坂井剛, 廣田朋也, "Unbiased Chemical Survey of Protostellar Sources in Perseus III", P121a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

4) Yichen Zhang, Hector Arce, Diego Mardones, Nami Sakai, Sylvie Cabrit, Michael Dunham, Guido Garay, Alberto Noriega-Crespo, Stella Offner, Alejandro Raga, Startt Corder, "Multiple Coherent Shell Structures Revealed by ALMA Observation of the HH6/47 Molecular Outflow", P130a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

5) 吉田健人, 坂井南美, 渡邊祥正, 山本智, "星形成領域における H_2CO の ^{13}C 同位体比の観測", P137a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

β Pictoris", NRO45m/ASTE Single Dish Science Workshop 2017, NAOJ Nobeyama Radio Observatory, Japan, 1-2 Aug. 2017

4) Nami Sakai, "Tracing chemistry toward protoplanetary disks by ALMA", The XXIV International Symposium of Free Radicals (ISFR2017), The International Free Radicals Symposium Committee, Hayama, Japan, 27 Aug. – 1 Sept. 2017

5) Nami Sakai, Yoko Oya, Muneaki Imai, Satoshi Yamamoto, Yichen Zhang, Aya Higuchi, Cecilia Ceccarelli, Bertrand Lefloch, Charlotte Vastel, Ana Lopez-Sepulcre, Tomoyuki Hanawa, Yuri Aikawa, Takeshi Sakai, Tomoya

Hirota, “Disk Formation: Observational Challenge”, ALMA Long Baseline Workshop, Mielparque Kyoto, Japan, 3-5 Oct. 2017

6) Aya Higuchi, Nami Sakai, Ana Lopez-Sepulcre, Yoko Oya, Muneaki Imai, Kento Yoshida, Yoshimasa Watanabe, Yichen Zhang, Takeshi Sakai, Tomoya Hirota, Satoshi Yamamoto, “Unbiased Chemical Survey of Protostellar Sources in Perseus”, ALMA Workshop 2017, Star Formation with ALMA: Evolution from dense cores to protostar, NAOJ, Mitaka, Japan, 26 Oct. 2017

7) Aya Higuchi, Nami Sakai, Aki Sato, Takeshi Tsukagoshi, Munetake Momose, Kazunari Iwasaki, Hiroshi Kobayashi, Daisuke Ishihara, Hidehiro Kaneda and Satoshi Yamamoto, “Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris”, 10th RESCEU/Planet2 Symposium, Planet Formation around Snowline, University of Tokyo, Japan, 28-30 Nov. 2017

8) Nami Sakai, “Chemical History of Young Sun-like Stars: Why are we here?”, International Symposium on the Development of Life -Unfolding with interdisciplinary views-, University of Miyazaki, Japan, 11, Dec. 2017

9) Aya Higuchi, Nami Sakai, Aki Sato, Takeshi Tsukagoshi, Munetake Momose, Kazunari Iwasaki, Hiroshi Kobayashi, Daisuke Ishihara, Hidehiro Kaneda and Satoshi Yamamoto, “Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris”, ALMA /45m/ASTE Users Meeting 2017, NAOJ, Mitaka, Japan, 26-27 Dec. 2017

国内会議

1) 坂井南美, “科学で探る円盤形成”, 地球惑星連合大会, アルマによる惑星科学の新展開, 幕張メッセ, 千葉, 2017 年 5 月 24 日

2) 坂井南美, 花輪知幸, Yichen Zhang, 樋口あや, 大屋瑶子, 山本智, “Disk Structure around the Class 0 Protostar in L1527”, P107a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

3) 樋口あや, 坂井南美, 大屋瑶子, 今井宗明, 山本智, 渡邊祥正, Ana Lopez-Sepulcre, 坂井剛, 廣田朋也, “Unbiased Chemical Survey of Protostellar Sources in Perseus III”, P121a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

4) Yichen Zhang, Hector Arce, Diego Mardones, Nami Sakai, Sylvie Cabrit, Michael Dunham, Guido Garay, Alberto Noriega-Crespo, Stella Offner, Alejandro Raga, Startt Corder, “Multiple Coherent Shell Structures Revealed by ALMA Observation of the HH6/47 Molecular Outflow”, P130a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

5) 吉田健人, 坂井南美, 渡邊祥正, 山本智, “星形成領域における H_2CO の ^{13}C 同位体比の観測”, P137a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

6) 大橋聡史, 立松健一, 神鳥亮, Patricio Sanhueza, 廣田朋也, Quang Nguyen Luong, Minho Choi, “ALMA observation of part of filaments in the Orion A cloud for the initial conditions of star formation”, P123a, 日本天文学会 2017 年秋季年会, 北海道大学, 札幌市, 2017 年 9 月 11-13 日

7) 大橋聡史, 片岡章雅, 永井洋, 深川美里, 花輪知幸, 百瀬宗武, 塚越崇, 村川幸史, 武藤恭之, 芝井広, “ALMA polarization observation toward the protoplanetary disk around HD142527”, P203a, 日本天文学会 2018 年春季年会, 千葉大学, 千葉市, 2018 年 3 月 14-16 日

8) 吉田健人，坂井南美，渡邊祥正，山本智，“星形成領域 L1527 における H_2CO の重水素化物の ALMA 観測”, P112a, 日本天文学会 2018 年春季年会，千葉大学，千葉市，2018 年 3 月 14-16 日

9) Yichen Zhang, Nami Sakai, Aya Higuchi, Ana Lopez-Sepulcre, Yoko Oya, Muneaki Imai, Takeshi Sakai, Yoshimasa Watanabe, Kento Yoshida, Bertran Lefloch, Cecilia Ceccarelli, Satoshi Yamamoto,“Protostellar Outflows in the Perseus Molecular Clouds”, P121a, 日本天文学会 2018 春季年会，千葉大学，千葉市，2018 年 3 月 14-16 日

10) 千葉雄太郎，坂井南美，海老澤勇治，山本智，吉田健人，渡邊祥正，酒井剛，“サブミリ波帯実験室分子分光計の開発と初期成果”, V152a, 日本天文学会 2018 年春季年会，千葉大学，千葉市，2018 年 3 月 14-16 日

11) Aya Higuchi, Atsushi Nishimura, Tetsuo Hasegawa, Kazuya Saigo, Patricio Sanhueza, James Chibueze, “ALMA reveals a hub of filamentary molecular clouds in Sgr B2(N) II”, P117a, 日本天文学会 2018 年春季年会，千葉大学，千葉市，2018 年 3 月 14-16 日

Posters

1) Satoshi Ohashi, Patricio Sanhueza, Tomoya Hirota, Minho Choi, Quang Nguyen Luong, Kenichi Tatematsu, “Multiple star formation of a starless core being part of a filament in the Orion A cloud”, Francesco's Legacy Star Formation in Space and Time, Firenze, Italy, 5-9 Jun. 2017

2) Yutaro Chiba, Nami Sakai, Yuji Ebisawa, Kento Yoshida, Yoshimasa Watanabe, Takeshi Sakai, and Satoshi Yamamoto, “A newterahertz emission spectrometer at RIKEN”, 34th International Symposium on Free Radicals, Hayama, Japan, 29 Aug. 2017

3) Yichen Zhang, Jonathan Tan, “A SED Model Grid for Massive Star Formation”, 日本天文学会 2017 年秋季年会，北海道大学，札幌市，日本，2017 年 9 月 11-13 日

4) Nami Sakai, “Chemical Diversity of Protostellar Systems: Are we alone?”, Japanese-American -German Frontiers of Science Symposium, Bad Neuenahr, Germany, 21-24 Sept. 2017

5) Yutaro Chiba, Nami Sakai, Yuji Ebisawa, Kento Yoshida, Yoshimasa Watanabe, Takeshi Sakai, and Satoshi Yamamoto, “A New Emission Spectrometer at RIKEN”, Laboratory Astrophysics Workshop 2017, Bonn, Germany, 29 Nov. - 1 Dec. 2017

Books, proceedings and others

1) 日本天文学会 天文月報 “化学組成で探る原始星円盤の形成過程” 2017 年 5 月号

2) **Developed code**: An SED model grid and fitting tool for massive star formation, available for the community to use. (https://doi.org/10.5281/zenodo.1045606)

Press release

1) Aya E. Higuchi, Aki Sato, Takashi Tsukagoshi, Nami Sakai, Kazunari Iwasaki, Munetake Momose, Hiroshi Kobayashi, Daisuke Ishihara, Sakae Watanabe, Hidehiro Kaneda and Satoshi Yamamoto, “若い惑星系に残るガスは塵から供給された －炭素原子ガスの検出で分かったガスの起源－/Detection of Submillimeter-wave [C I]

Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris", 理研・茨城大学・名古屋大学共同研究, 10 Apr. 2017

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3) 科学研究費補助金 [新学術領域研究(研究領域提案型)]宇宙における分子進化：星間雲から原始惑星系へ(代表：香内晃) 計画研究：原始惑星系の化学的多様性とその進化(代表：山本智) 2013-2017

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