

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, Protoplanetary 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.

1. Overview

In formation of a solar-type (low-mass) star, a rotationally supported disk is formed around the protostar, and is eventually evolved into a planetary system. A detailed understanding of this process is essential in exploring the origin of the Solar System, and hence, it is recognized as one of the principal targets of astronomy and astrophysics. Now such a disk structure is known to exist in the Class I protostars and even in some Class 0 protostars on the basis of interferometric observations of the rotational emission of CO and its isotopologues including those with Atacama Large Millimeter/submillimeter Array (ALMA). However, it is still controversial when and how a rotationally supported disk is formed.

In addition, a comprehensive understanding of chemical evolution from protostellar cores to protoplanetary disks is also important in relation to the origin of the Solar System. 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; a longer duration time favors hot corino chemistry. More interestingly, how is this chemical diversity brought into protoplanetary disks and planetary systems? Now, ALMA is ready to answer this important question.

We are conducting extensive observations of young protostellar sources with ALMA. Sub-arcsecond resolution images of various molecules are obtained toward a few representative sources, and totally unexpected physical and chemical features are being unveiled. The most important result is the discovery of the centrifugal barrier of the infalling-rotating envelope and drastic chemical change associated with it in L1527 (Sakai et al. 2014). In this study, we demonstrated that chemical approach is very powerful in exploring the disk formation around low-mass protostars. In L1527, the infalling-rotating envelope is traced by carbon-chain molecules and CS, while the centrifugal barrier is highlighted by SO. On the other hand, H₂CO traces from the envelope to the disk across the centrifugal barrier.

Following this discovery, we are extending our ALMA observations to (1) the WCCC source in more evolved stages (TMC-1A) and to (2) the hot corino source (IRAS 16293-2422). Also we have succeeded to obtain the ALMA time (Cycle 3) for the extensive chemical survey of 37 protostellar cores in the Perseus molecular cloud. With these observations, we are going to investigate physical and chemical processes occurring in the disk forming zone. In addition to the above ALMA studies, we studied the ¹³C anomaly of c-C₃H₂ in L1527, which is an important tracer to bridge between interstellar chemistry and planetary chemistry. This result will be an important base for requesting the ALMA time. We also studied formation mechanism of CH₃OH in the cold dark cloud TMC-1. The grain origin of this molecule is further confirmed by its spatial distribution and the ¹³C isotope ratio. Furthermore, we conducted observations of the OH 18 cm transition toward three molecular clouds, and found that this transition can be a good thermometer of diffuse molecular gas. This will be a new probe to study the formation processes of molecular clouds, which may be eventually related to the origin of the chemical diversity found in the protostellar cores. Finally, we are now constructing the submillimeter-wave spectrometer to measure rest frequencies of rotational transitions of molecules with astronomical interest. More details of these results are described below.

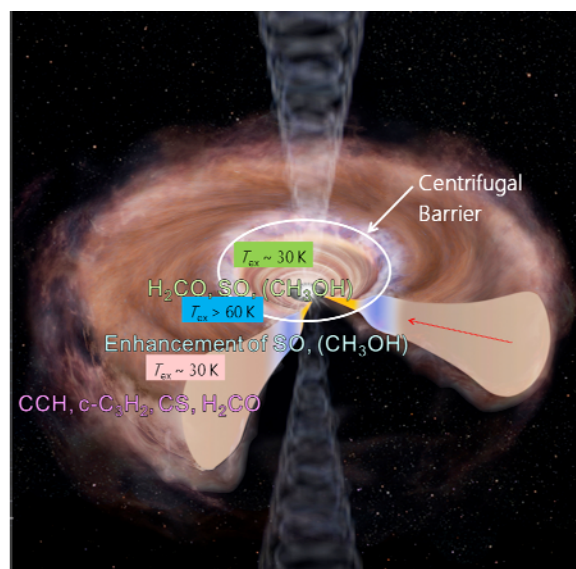


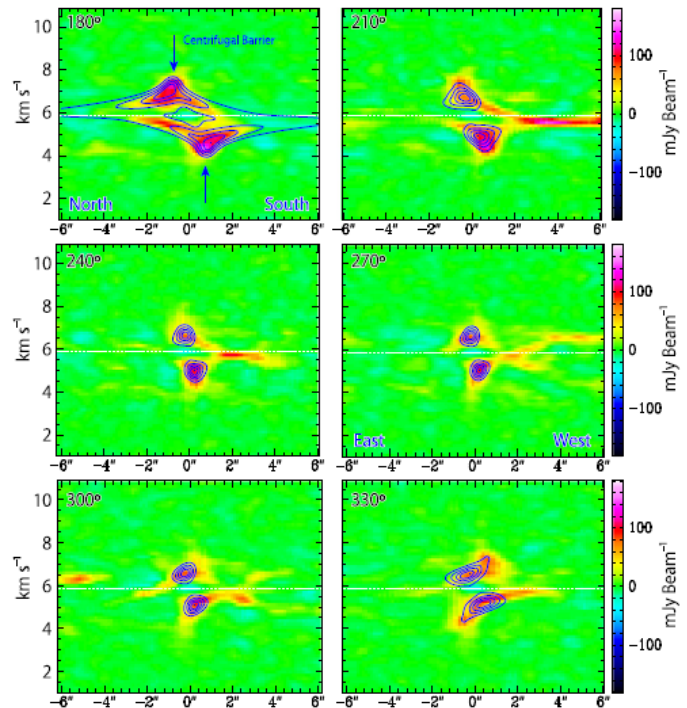
Fig 1. Schematic illustration of infalling-rotating envelope, centrifugal barrier, and disk system.

2. ALMA Observation of the Infalling-Rotating Envelope and the Outflow in L1527

We studied sub-arcsecond-resolution images of the rotational spectral emissions of CS observed toward a low-mass Class 0/I protostar IRAS 04368+2557 in L1527 with ALMA. This source is a prototypical warm-carbon-chain-chemistry (WCCC) source characterized by rich existence of carbon-chain molecules. The distribution of CS consists of an envelope component around the protostar and a faint butterfly shaped outflow component. The kinematic structure of the flattened envelope, which has almost edge-on configuration, is well reproduced by a simple ballistic model of an infalling-rotating envelope. In this analysis, the inclination angle of the flattened envelope is constrained to be 5° , where the western side of the envelope is found to face the observer. This configuration is opposite to the direction of the large-scale ($\sim 10^4$ AU) outflow suggested previously, and to the morphology of infrared reflection near the protostar (~ 200 AU). The latter discrepancy could originate from high extinction by the outflow cavity of the western side, or may indicate that the outflow axis is not parallel to the rotation axis of the envelope. The kinematic structure of the small-scale outflow component observed with CS can be well interpreted by a standard parabolic outflow model using the inclination angle derived above. The different orientation of the outflow between the small and large scale implies a possibility of precession of the outflow axis.

Reference: #7 in the publication list

Fig 2. PV diagrams of CS ($J=5-4$; color). 180° and 270° corresponds to envelope and outflow direction, respectively. The blue contours represent the infalling rotating envelope model with the inclination angle of $+5^\circ$. Contours are every 20% of the peak intensity.



3. Centrifugal Barrier of the Infalling-Rotating Envelope of the Class I Protostar TMC-1A

Sub-arcsecond images of the rotational line emission of CS and SO have been obtained toward the Class I protostar IRAS 04365+2535 in TMC-1A with ALMA. This source is an evolved WCCC source. A compact (a few 100 AU scale) component around the protostar is clearly detected in the CS and SO emission. The kinematic structure of the compact component of CS clearly reveals infalling-rotating motion conserving the angular momentum. The position velocity diagrams are well explained by a ballistic model of an infalling-rotating envelope, although the distribution of the infalling gas is asymmetric around the protostar. Under this simple model, the radius of the centrifugal barrier (a half of the centrifugal radius) of the infalling-rotating envelope and the inclination angle of the disk (0° for edge-on) are estimated to be 40-60 AU and 20° , respectively. The distribution of SO is mostly concentrated around the radius of the centrifugal barrier, although it also shows asymmetry around the protostar. This result demonstrates that a drastic change in chemical composition of the gas infalling onto the protostar occurs around the radius of the centrifugal barrier even in the Class I source.

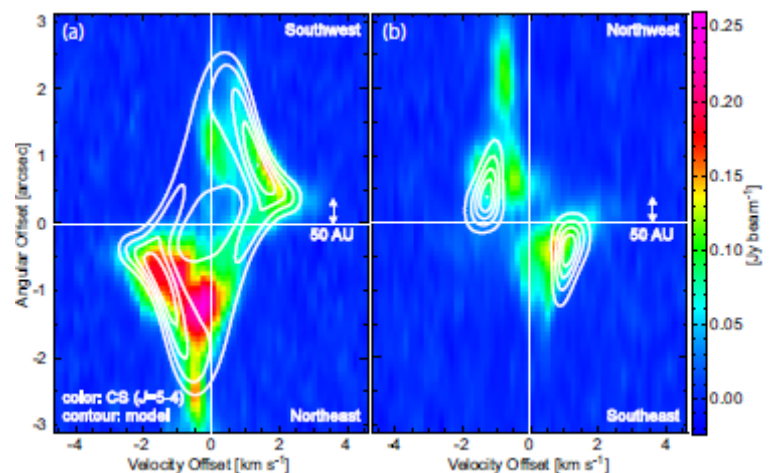


Fig. 3 PV diagram of CS ($J=5-4$) along the envelope, on which the result of the infalling-rotating envelope model is superimposed (contours).

Reference: #12 in the publication list

4. A few 100 AU Scale Chemical Composition and Dynamics of the Hot Corino Source IRAS16293-2422

We have analyzed rotational spectral line emission of OCS, CH₃OH, HCOOCH₃, and H₂CS observed toward the low-mass Class 0 protostellar source IRAS 16293-2422 Source A at a sub-arcsecond resolution (0."6 x 0."5) with ALMA. This source is a prototypical hot corino source characterized by rich existence of saturated organic molecules. In this observation, the 50 AU scale distribution is found to be different from molecule to molecule. The OCS line is recognized as a useful tracer to study the kinematic structure of the infalling-rotating envelope in this source. On the other hand, the CH₃OH and HCOOCH₃ distributions are found to be concentrated around the inner part of the infalling-rotating envelope. With the aid of a simple ballistic model of the infalling-rotating envelope, the radius of the centrifugal barrier and the protostellar mass are evaluated from the OCS data to be from 40 to 60 AU and from 0.5 to 1.0 M_{sun} , respectively. This is the first indication of the centrifugal barrier of the infalling-rotating envelope in a hot corino source. CH₃OH and HCOOCH₃ may be liberated from ice mantles due to weak accretion shocks of the infalling gas around the centrifugal barrier, and/or due to thermal heating from the protostar. The H₂CS emission seems to come from the disk component inside the centrifugal barrier in addition to the envelope component. The gas kinetic temperature measured by using multiple lines of H₂CS with different K_a is found to be enhanced around the centrifugal barrier, indicating weak accretion shocks and/or direct radiation heating the stagnated gas around the centrifugal barrier. Thus, the centrifugal barrier plays a central role not only in the formation of a rotationally-supported disk but also in the chemical evolution from the envelope to the protoplanetary disk.

5. ¹³C Isotope Anomaly of c-C₃H₂ in L1527

The rotational spectral lines of c-C₃H₂ and two kinds of the ¹³C isotopic species, c-¹³CCH₂ (C_{2v} symmetry) and c-CC¹³CH₂ (C_s symmetry), have been observed in the 1–3 mm band toward the WCCC source, L1527. We have detected 7, 3, and 6 lines of c-C₃H₂, c-¹³CCCH₂, and c-CC¹³CH₂, respectively, with the Nobeyama 45 m telescope and 34, 6, and 13 lines, respectively, with the IRAM 30 m telescope. With these data, we have evaluated the column densities of the normal and ¹³C isotopic species. The [c-C₃H₂]/[c-¹³CCCH₂] ratio is determined to be 310 ± 80 , while the [c-C₃H₂]/[c-CC¹³CH₂] ratio is to be 61 ± 11 . The [c-C₃H₂]/[c-¹³CCCH₂] and [c-C₃H₂]/[c-CC¹³CH₂] ratios expected from the elemental ¹²C/¹³C ratio are 60–70 and 30–35, respectively, and hence, this observation further confirms the dilution of the ¹³C species in carbon-chain molecules and their related molecules. It is most likely that this result originates from the dilution of ¹³C⁺ in the gas-phase C⁺ due to the isotope exchange reaction: ¹³C⁺ + CO → ¹³CO + C⁺. Moreover, the abundances of the two ¹³C isotopic species are different from each other. The ratio of c-¹³CCCH₂ species relative to c-CC¹³CH₂ is determined to be 0.20 ± 0.05 . If ¹³C were randomly substituted for the three carbon atoms, the [c-¹³CCCH₂]/[c-CC¹³CH₂] ratio would be 0.5. Hence, the observed ratio clearly indicates that c-CC¹³CH₂ exists more favorably.

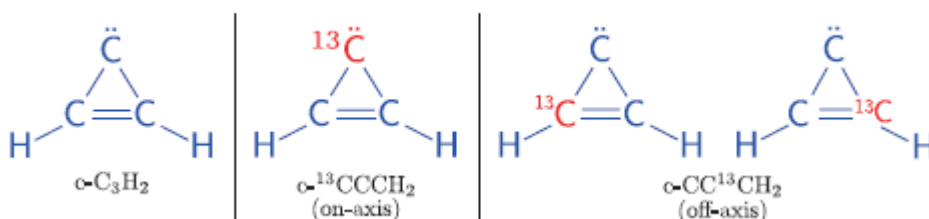


Fig 4. Molecular geometry of c-C₃H₂ and its ¹³C species.

Reference: #3 in the publication list

6. Origin of CH₃OH in TMC-1

To explore the formation mechanisms of gas phase CH₃OH in cold starless cores, we conducted high spectral resolution observations toward the cyanopolyynes peak of Taurus Molecular Cloud-1 (TMC-1 CP) with the IRAM 30 m telescope, the Green Bank Telescope, and the Nobeyama 45 m telescope. The spectral lines of CH₃OH toward TMC-1 CP are found to have a double-peaked profile separated by 0.5 km s⁻¹. The spectral line profile of CH₃OH is much different from those of C³⁴S, C₃S, and HC₇N observed toward this source. The H₂ densities of the

emitting region of CH₃OH for the blueshifted and redshifted components are derived to be $(1.7 \pm 0.5) \times 10^4 \text{ cm}^{-3}$ and $(4.3 \pm 1.2) \times 10^4 \text{ cm}^{-3}$, respectively. These densities are similar to or slightly lower than those found for the other molecules. These results suggest a chemical differentiation between CH₃OH and the other molecules, which was indeed confirmed by mapping observations of the CH₃OH and C³⁴S lines. These results are consistent with the general idea that CH₃OH is formed on dust grains and is liberated into the gas phase by nonthermal desorption. The grain-surface origin of CH₃OH is further confirmed by the CH₃OH/¹³CH₃OH ratio. Weak shocks caused by accreting diffuse gas to the TMC-1 filament, photoevaporation caused by cosmic-ray induced UV radiation, and the desorption of excess reaction energy in the formation of CH₃OH on dust grains are possible desorption mechanisms.

Reference: #1 in the publication list

7. OH 18cm Transition as a Thermometer for Molecular Clouds

The four hyperfine components of the 18 cm OH transition were observed toward the translucent cloud eastward of Heiles Cloud 2 (HCL2E), the cold dark cloud L134N, and the photodissociation region of the ρ -Ophiuchi molecular cloud with the Effelsberg 100 m telescope. Intensity anomalies among the hyperfine components were found in all three regions. In particular, an absorption feature of the 1612 MHz satellite line against the cosmic microwave background was detected toward HCL2E and two positions of the ρ -Ophiuchi molecular cloud. On the basis of statistical equilibrium calculations, we find that the hyperfine anomalies originate from the non-LTE population of the hyperfine levels, and can be used to determine the kinetic temperature of the gas over a wide range of H₂ densities (10^2 – 10^7 cm^{-3}). Toward the center of HCL2E, the gas kinetic temperature is determined to be $53 \pm 1 \text{ K}$, and it increases toward the cloud peripheries ($\sim 60 \text{ K}$). The ortho-to-para ratio of H₂ is determined to be 3.5 ± 0.9 . In L134N, a similar increase of the temperature is also seen toward the periphery. In the ρ -Ophiuchi molecular cloud, the gas kinetic temperature decreases as a function of the distance from the exciting star HD 147889. These results demonstrate a new aspect of the OH 18 cm line that can be used as a good thermometer of molecular cloud envelopes. The OH 18 cm line can be used to trace a new class of warm molecular gas surrounding a molecular cloud, which is not well traced by the emission of CO and its isotopologues.

8. Molecular Spectroscopy of Interstellar Molecules

We are planning to develop the submillimeter-wave spectrometer for accurate measurements of rotational transition frequencies of various organic molecules with astronomical interest. Thanks to recent developments of radioastronomy, less abundant species including isotopologues are readily detected in molecular clouds and star forming regions. In order to conduct detailed analyses of the kinematic structure of the source as demonstrated above, rest frequencies of rotational transitions have to be as accurate as a few 10 kHz, at least. However, the accuracy of the rest frequencies is often worse than that, which makes the astronomical interpretation difficult. With this in mind, we are developing a new spectrometer observing ‘emission’ of rotational transitions of molecules by using the receiver technology developed for radioastronomy. We employ the SIS and HEB receivers as the front end, and the digital correlators as the back end. We designed the spectrometer, and purchased the digital correlators. In the next year, we expect the first laboratory spectrum with this spectrometer.

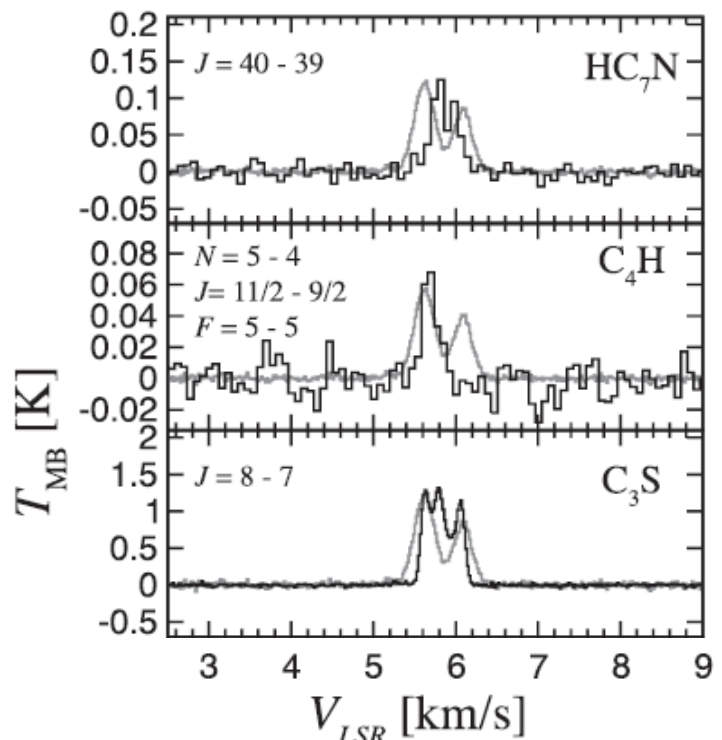


Fig 5. Spectral line profiles of HC₇N, C₄H, C₃S, (thick line) in TMC-1 CP superposed on that of CH₃OH ($1_{0,1} - 0_{0,0}$ A+; thin line).

Oral Presentations

Invited (International)

- 1) 6th International Workshop on Electrostatic Storage Devices, June 8-11, 2015, Tokyo, Japan: "Observational Studies on Molecular Evolution in Star and Planet Forming Regions"
- 2) 3rd DTA Symposium, The Origins of Planetary Systems: from the Current View to New Horizons: "Protostellar Disk Formation Traced by Chemistry"
- 3) Protoplanetary Disk Dynamics and Planet Formation, Sep. 29-Oct. 2, 2015, Yokohama, Japan: "Disks and Outflow System in Low-Mass Protostellar Sources"

Contributed

- 1) 坂井南美, Ana Lopez-Sepulcre, 大屋瑤子, 今井宗明, 渡邊祥正, 山本智, 酒井剛, 廣田朋也, "Unbiased Chemical Survey of Protostellar Sources in Perseus", P124a, 日本天文学会, 甲南大学, 2015年9月9-11日

Seminar

- 1) RIBF Nuclear Physics Seminar, Jul. 14, 2015, Wako, RIKEN, Japan: "Astrochemical Approach to Star and Planet Formation"

Publications (Refereed)

- 1) "Methanol in the Starless Core, Taurus Molecular Cloud-1", Tatsuya Soma, Nami Sakai, Yoshimasa Watanabe, and Satoshi Yamamoto, 2015, ApJ, 802, 74.
- 2) "ALMA Observations of the IRDC Clump G34.43+00.24 MM3: DNC/HNC Ratio", Takeshi Sakai, Nami Sakai, Kenji Furuya, Yuri Aikawa, Tomoya Hirota, Jonathan B. Foster, Patricio Sanhueza, James M. Jackson, and Satoshi Yamamoto, 2015, ApJ, 803, 70.
- 3) "Abundance Anomaly of the ^{13}C Isotopic Species of $\text{c-C}_3\text{H}_2$ in the Low-Mass Star Formation Region L1527", Kento Yoshida, Nami Sakai, Tomoya Tokudome, Ana López-Sepulcre, Yoshimasa Watanabe, Shuro Takano, Bertrand Lefloch, Cecilia Ceccarelli, Rafael Bachiller, Emmanuel Caux, Charlotte Vastel, and Satoshi Yamamoto, 2015, ApJ, 807, 66.
- 4) "Spectral Line Survey toward the Young Massive Protostar NGC2264 CMM3 in the 4 mm, 3mm, and 0.8 mm Bands", Yoshimasa Watanabe, Nami Sakai, Ana López-Sepulcre, Ryuta Furuya, Takeshi Sakai, Tomoya Hirota, Sheng-Yuan Liu, Yu-Nung Su, and Satoshi Yamamoto, 2015, ApJ, 809, 162.
- 5) "Probing the effects of external irradiation on low-mass protostars through unbiased line surveys", Lindberg, J. E., Jørgensen, J. K., Watanabe, Y., Bisschop, S. E., Sakai, N., and Yamamoto, S., 2015, A&A, 584, 28.
- 6) "Spectral-line Survey at Millimeter and Submillimeter Wavelengths toward an Outflow-shocked Region, OMC 2-FIR 4", Shimajiri, Yoshito, Sakai, Takeshi, Kitamura, Yoshimi, Tsukagoshi, Takashi, Saito, Masao, Nakamura, Fumitaka, Momose, Munetake, Takakuwa, Shigehisa, Yamaguchi, Takahiro, Sakai, Nami, Yamamoto, Satoshi, Kawabe, Ryohei, 2015, ApJS, 221, 31.
- 7) "Geometric and Kinematic Structure of the Outflow/Envelope System of L1527 Revealed by Subarcsecond-Resolution Observation of CS", Yoko Oya, Nami Sakai, Bertrand Lefloch, Ana López-Sepulcre, Yoshimasa Watanabe, Cecilia Ceccarelli, and Satoshi Yamamoto, 2015, ApJ, 812, 59.
- 8) "OH 18 cm Transition as a Thermometer for Molecular Clouds", Yuji Ebisawa, Hiroshi Inokuma, Nami Sakai, Karl M. Menten, Hiroyuki Maezawa, and Satoshi Yamamoto, 2015, ApJ, 815, 13.
- 9) "Spectral Line Survey toward Molecular Clouds in the Large Magellanic Cloud", Yuri Nishimura, Takashi Shimonishi, Yoshimasa Watanabe, Nami Sakai, Yuri Aikawa, Akiko Kawamura, and Satoshi Yamamoto, 2015, ApJ, accepted.
- 10) "Spectral Line Survey toward Molecular Clouds in the Large Magellanic Cloud", Yuri Nishimura, Takashi Shimonishi, Yoshimasa Watanabe, Nami Sakai, Yuri Aikawa, Akiko Kawamura, Satoshi Yamamoto, 2015, ApJ, Accepted.
- 11) "Implication of Formation Mechanisms of HC_3N in TMC-1 as Studied by ^{13}C Isotopic Fractionation", Kotomi Taniguchi, Hiroyuki Ozeki, Masao Saito, Nami Sakai, Fumitaka Nakamura, Seiji Kamenno, Shuro Takano, Satoshi Yamamoto, 2015, ApJ, Accepted.
- 12) "Subarcsecond Analysis of Infalling-Rotating Envelope around the Class I Protostar IRAS 04365+2535", Nami Sakai, Yoko Oya, Ana Lopez-Sepulcre, Yoshimasa Watanabe, Takeshi Sakai,

Tomoya Hirota, Yuri Aikawa, Cecilia Ceccarelli, Bertrand Lefoch, Emmanuel Caux, Charlotte Vastel, Claudine Kahane, and Satoshi Yamamoto, 2015, submitted to ApJ.

13) “The role of SiO as a tracer of past star-formation events: The case of the high-mass protocluster NGC2264-C”, Ana Lopez-Sepulcre, Yoshimasa Watanabe, Nami Sakai, Ryuta Furuya, Osamu Saruwatari, and Satoshi Yamamoto, 2015, submitted to ApJ.

14) “Molecular Distribution in the Spiral Arm of M51”, Yoshimasa Watanabe, Nami Sakai, Kazuo Sorai, Junko Ueda, and Satoshi Yamamoto, 2015, ApJ, Accepted.

Laboratory members list

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