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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

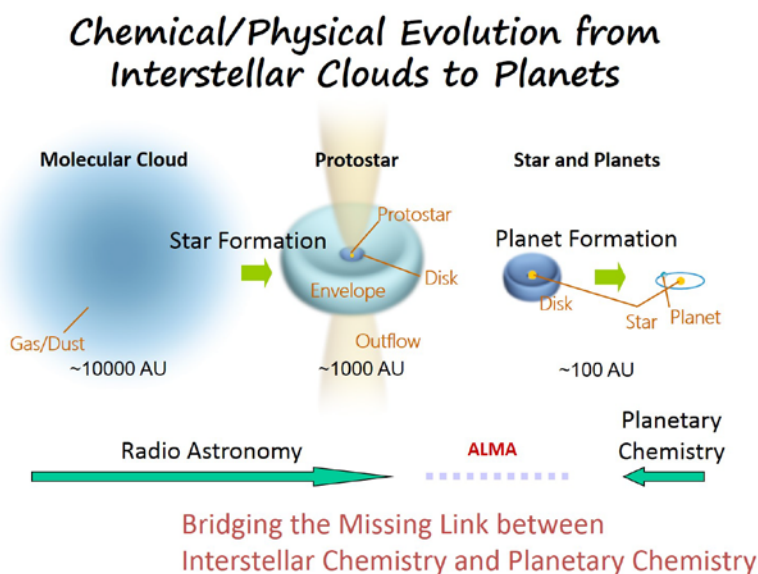
In formation of a solar-type (low-mass) star, a rotationally supported disk is formed around the protostar, and is eventually evolved into a planetary system. A detailed understanding of this process is essential in exploring the origin of the Solar System, and hence, it is recognized as one of the principal 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.

The centrifugal barrier was then identified in a few other young stellar objects. Around the Class I protostar in TMC-1A (WCCC type), the CS emission clearly traces the infalling-rotating envelope, while the SO emission selectively traces the centrifugal barrier. Although the distributions of CS and SO are asymmetric around the protostar, the essential feature of the chemical differentiation is similar to the L1527 case. With the aid of the ballistic model, the radius of the centrifugal barrier is determined to be 50 au. The gas certainly keeps falling beyond the centrifugal radius (100 au) in this source (Sakai et al. 2016). Another WCCC source IRAS15398-3359 shows a similar trend (Oya et al. 2014). In this source, the CCH and H₂CO distributions were studied. The both molecules traces the disk/envelope component as well as the outflow cavity. The integrated intensity distribution of the CCH emission shows a marginal dip toward the protostar, while that of H₂CO has a clear peak at the protostar. This trend is consistent with that found in L1527, although the velocity gradient was not detected clearly at a resolution of 0.5", because of the small protostar mass and the small radius of the centrifugal barrier. The rotating ring traced by the SO emission is also found for L1489 by Yen et al. (2014). This source is a Class I protostar in Taurus, and the Keplerian disk structure is reported. The position velocity diagram of SO shows a bar-like feature, indicating the rotating ring with the radius of 300 au. Unfortunately, no carbon-chain molecules and CS were observed for this source, and the infalling-rotating envelope was not characterized. Nevertheless, the SO ring may trace the centrifugal barrier, as in the case of L1527 and TMC-1A. Thus, the existence of the centrifugal barrier and the chemical change there could be more general phenomena.



Following these studies, we are extending our ALMA observations to the hot corino sources, (2) IRAS 16293-2422A and (3) NGC1333IRAS4A, as well as hybrid chemical-type sources, (4) L483 and (5) B335, in relation to the disk formation. In relation to the above ALMA studies on disk formation, understanding the mechanism of angular momentum extraction is important to form protostar and keplerian disk. Thus, we have also studied molecular outflow (6) in Intermediate-mass protostellar source, HH46/47. Furthermore, we have conducted very high angular resolution observation toward L1527 to understand what is going on around the centrifugal barrier (7). In addition, we studied the deuterium fractionation of H₂CO in the prototypical WCCC source L1527(8). This helps us to understand fundamental chemistry occurring in star forming cores. Finally, we studied the origin of gas detected in debris disks around main sequence of slightly younger stars, to judge the gas is primordial or secondary origin (9). This study helps us to understand the future of the chemistry found in protostellar/protoplanetary disks.

1. ALMA observation of the hot corino source, IRAS16293-2422A (Led by Oya & Sakai)

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 ($\sim 0.6'' \times 0.5''$) with ALMA. Significant chemical differentiation is found on a scale of 50 au. The OCS line is found to trace well the infalling–rotating envelope in this source. On the other hand, the distributions of CH₃OH and HCOOCH₃ are found to be concentrated around the inner part of the infalling–rotating envelope. With a simple ballistic model of the infalling–rotating envelope, the radius of the centrifugal barrier (a half of the centrifugal radius) and the protostellar mass are evaluated from the OCS data to be from 40 to 60 au and from 0.5 to 1.0M_⊙, respectively, assuming the inclination angle of the envelope/disk structure to be 60° (90° for the edge-on configuration). Although the protostellar mass is correlated with the inclination angle, the radius of the centrifugal barrier is not. 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 by weak accretion shocks around the centrifugal barrier and/or by protostellar heating. The H₂CS emission seems to come from the disk component inside the centrifugal barrier in addition to the envelope component. 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.

Reference: #4 in the publication list

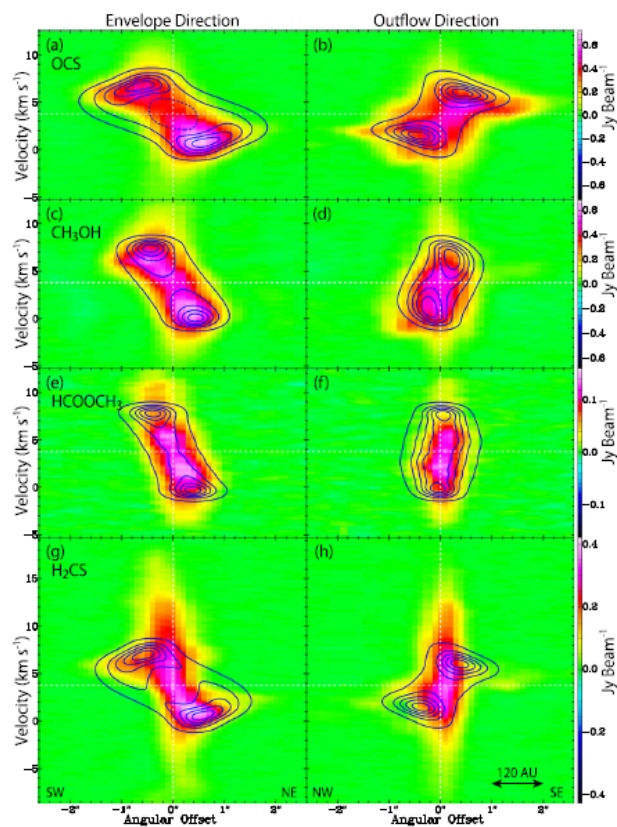


Fig 2. PV diagram along the envelope of IRAS16293-2422A. Blue contours represent the results of the infalling-rotating envelope models, where $M = 0.75 M_{\odot}$, $r_{CB} = 50$ au, and $i = 60^{\circ}$. The outer radii of the envelope (R) in the models for OCS, CH₃OH, HCOOCH₃, and H₂CS are 180, 80, 55, and 150 au, respectively. The contour levels are every 20% from 5% of each peak intensity.

2. ALMA observation of the hot corino source, NGC1333IRAS4A (Led by Lopez-Sepulcre & Sakai)

Hot corinos are extremely rich in complex organic molecules (COMs). Accurate abundance measurements of COMs in such objects are crucial to constrain astrochemical models. In the particular case of close binary systems this can only be achieved through high angular resolution imaging. We aim to perform an interferometric study of multiple COMs in NGC1333 IRAS 4A, a protostellar binary hosting hot corino activity, at an angular resolution that is sufficient to easily distinguish the emission from the two cores, separated by $1.8''$. We used the Atacama Large (sub-)Millimeter Array (ALMA) in its 1.2mm band to image, with an unprecedented angular resolution of $0.5''$, the emission from 10 different organic molecules in IRAS 4A. This allowed us to clearly disentangle the two protostellar cores present, A1 and A2. For the first time, we were able to derive the column densities and fractional abundances simultaneously for the two objects, allowing us to analyse the chemical differences between them. Molecular emission from organic molecules is concentrated exclusively in A2, while A1 appears completely devoid of COMs or even simpler organic molecules such as HNC 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 difference in the amount of COMs present in A1 and A2 is huge, ranging between a factor ~ 20 and ~ 300 . We estimate that the size of a hypothetical hot corino in A1 should be less than 10 au.

Our results favour a scenario in which the protostar in A2 is either more massive and/or subject to a higher accretion rate than A1, as a result of inhomogeneous fragmentation of the parental molecular clump. This naturally explains the smaller current envelope mass in A2 with respect to A1, as well as its molecular richness. The extremely low abundances of organic molecules in A1 demonstrate that the dense inner regions of a young protostellar core that has not yet formed a hot corino may be much poorer in COMs than the outer protostellar envelope. Finally, our results suggest that IRAS 4A is most likely a chemically younger version of the protostellar binary IRAS 16293–2422. The emissions are not well resolved and so it is difficult to study whether the COMs exist mainly around the centrifugal barrier as in the case of IRAS16293-2422 or not. Nevertheless, all those are concentrated around the protostar(A1), suggesting similar situation to that in IRAS16293-2422.

Reference: #16 in the publication list

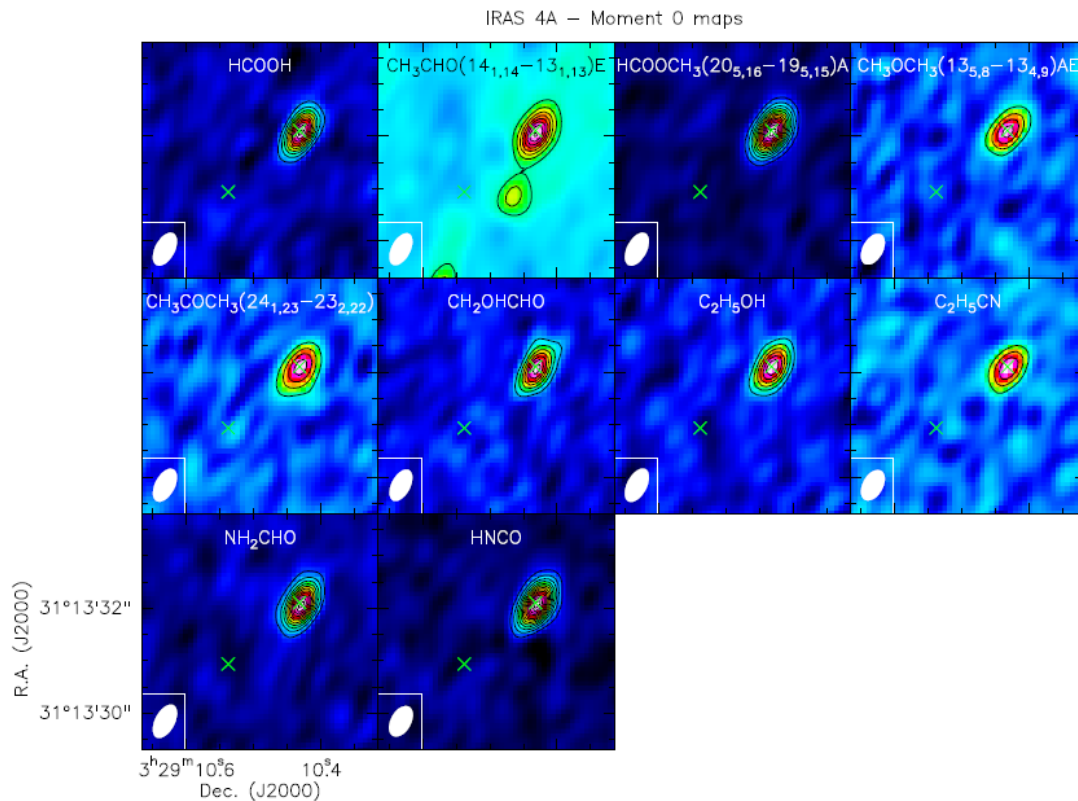


Fig. 3 Moment 0 maps of representative molecular lines. The transition is specified if more than one line from the same species was detected. The continuum peak position of the two protostellar cores A1 and A2 are marked with green crosses. Contours start at 5 sigma and increase by steps of 5 sigma in all the maps. The synthesised beam is depicted in white on the lower-left corner.

3. 2. ALMA Observation of the isolated star-forming core, B335 (Led by Imai & Sakai)

We have observed the low-mass Class 0 protostar IRAS 19347+0727 in B335 by using ALMA in the 1.2 mm band. Saturated complex organic molecules (COMs), CH₃CHO, HCOOCH₃, and NH₂CHO, are detected in a compact region within a few 10 au around the protostar. Additionally, CH₃OCH₃, C₂H₅OH, C₂H₅CN, and CH₃COCH₃ are tentatively detected. Thus, this is the first evidence of a hot corino in a Bok globule. Carbon-chain related molecules, CCH and c-C₃H₂, are also found in this source, whose distributions are extended over a scale of a few 100 au. On the other hand, sulfur-bearing molecules CS, SO, and SO₂ have both compact and extended components. Fractional abundances of the COMs relative to H₂ are found to be comparable to those in known hot corino sources. Though the COMs lines are as broad as 5–8 km s⁻¹, they do not show obvious rotation motion in the present observation. Thus, the COMs mainly exist in a structure whose distribution is much smaller than the synthesized beam (0.58"x0.52").

Reference: #7 in the publication list

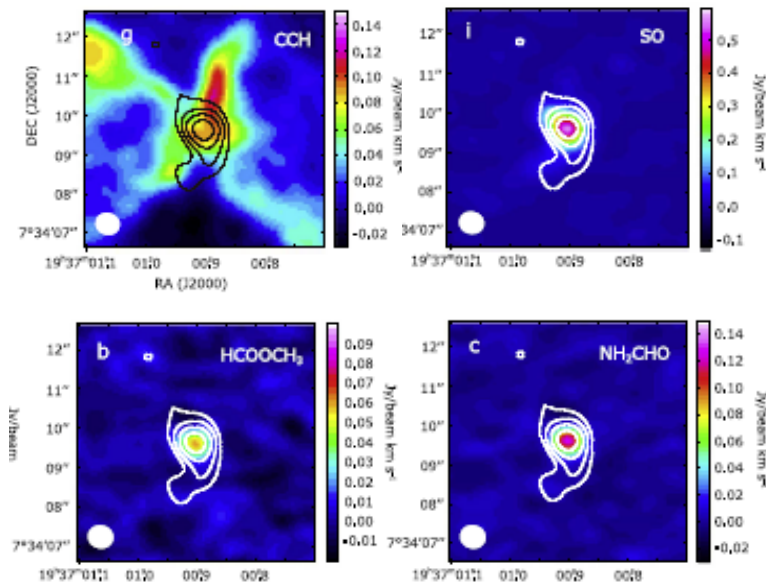


Fig.4 The continuum map and the moment 0 maps of CCH ($N=3-2$, $J=5/2-3/2$, $F=3-2$), SO ($N_J=6_7-5_6$), HCOOCH₃ ($20_{5,16}-19_{5,15}$), and NH₂CHO ($12_{0,12}-11_{0,11}$). The contours represent the continuum flux of 10σ , 20σ , 40σ , 80σ levels, where σ is $0.3 \text{ mJy beam}^{-1}$. Compared with the synthesized beam size shown in the bottom left of each figure, distributions of COMs are not resolved. The velocity range is $7.02-9.46 \text{ km s}^{-1}$ for CCH, $6.69-9.27 \text{ km s}^{-1}$ for SO, $5.06-11.67 \text{ km s}^{-1}$ for HCOOCH₃, and $5.20-10.22 \text{ km s}^{-1}$ for NH₂CHO, $2.85-13.66 \text{ km s}^{-1}$.

5. L483: Warm Carbon-Chain Chemistry Source Harboring Hot Corino Activity (Led by Oya & Sakai)

The Class 0 protostar, L483, has been observed in various molecular lines in the 1.2 mm band at a subarcsecond resolution with ALMA. An infalling-rotating envelope 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 HCOOCH₃ 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 NH₂CHO and HCOOCH₃ 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.

Reference: #13 in the publication list

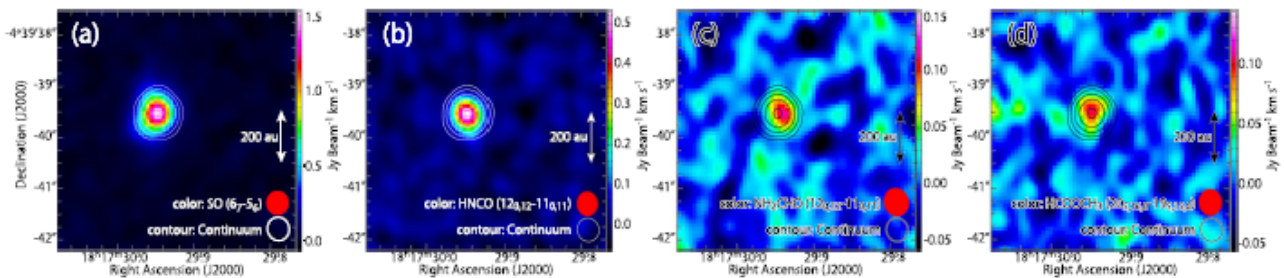
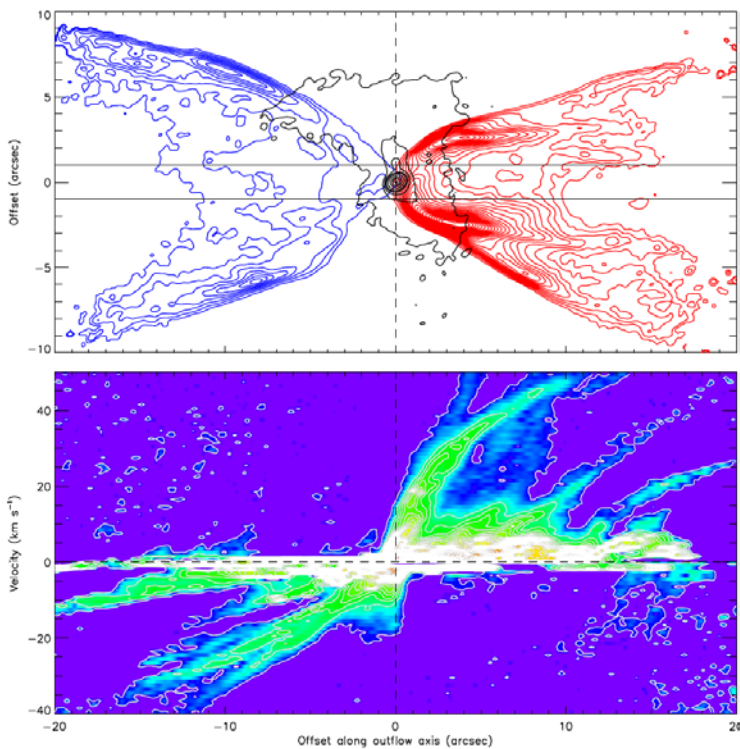


Fig.5 Integrated intensity maps of (a) SO ($J_N=6_7-5_6$), (b) HNCO ($12_{0,12}-11_{0,11}$), (c) NH₂CHO ($12_{0,12}-11_{0,11}$), and (d) HCOOCH₃ ($20_{5,16}-19_{5,15}$; A). The contours represent the 1.2 mm continuum map, where the contour levels are 10σ , 20σ , 40σ , 80σ , and 160σ , where the rms level is $0.13 \text{ mJy beam}^{-1}$.

6. Molecular outflow in HH46/47: wide-angle disk wind (Led by Zhang)



The accretion disk drives fast MHD winds which usually contain two components, a collimated jet and a radially distributed wide-angle wind. These winds further entrain the ambient gas into a secondary outflow which is usually traced by various molecules. Because the accretion process is episodic, people expect that the jet and the wide-angle wind is also episodic. While episodic outbursts in jet has been seen before, episodicity in the wide-angle wind has not been seen. In ALMA cycle 3 we observed the HH 46/47 molecular outflow which is driven by a low-mass protostar. We detected multiple outflowing shells with wide opening angles which are well separated in the velocity space. With simple model fitting, we can explain these wide outflowing shells as results of entrainment of ambient gas by the wide-angle wind in multiple outburst

events. This is the first clear evidence that the wide-angle wind, same as the collimated jet, experiences episodicity, as expected by theories of episodic accretion and wind launching. The coherent entrained shells further implies that the wide-angle wind should be launched from a relatively narrow region on the disk, which put constraints on the wind launching mechanism.

Fig.6 Upper: Integrated emission map for the red-shifted and blue-shifted outflows (red and blue contours) overlaid with continuum emission (black), showing the multiple shell structures. Lower: the position-velocity diagram along the outflow axis. The multiple shells are well defined in the velocity space.

7. Resolving the Centrifugal Barrier in L1527 (Led by Sakai)

We have resolved for the first time the radial and vertical structure of the almost edge-on envelope/disk system of the low-mass Class 0 protostar L1527. For that, we have used ALMA observations with a spatial resolution of $0.25'' \times 0.13''$ and $0.37'' \times 0.23''$ at 0.8 mm and 1.2 mm, respectively. The L1527 dust continuum emission has a deconvolved size of 78 au x 21 au, and shows a flared disk-like structure. A thin infalling-rotating envelope is seen in the CCH emission outward of about 150 au, and its thickness is increased by a factor of 2 inward of it. This radius lies between the centrifugal radius (200 au) and the centrifugal barrier of the infalling-rotating envelope (100 au). The gas stagnates in front of the centrifugal barrier and moves toward vertical directions. SO emission is concentrated around and inside the centrifugal barrier. The rotation speed of the SO emitting gas is found to be decelerated around the centrifugal barrier. A part of the angular momentum could be extracted by the gas which moves away from the mid-plane around the centrifugal barrier. If this is the case, the centrifugal barrier would be related to the launching mechanism of low velocity outflows, such as disk winds.

Reference: #11 in the publication list

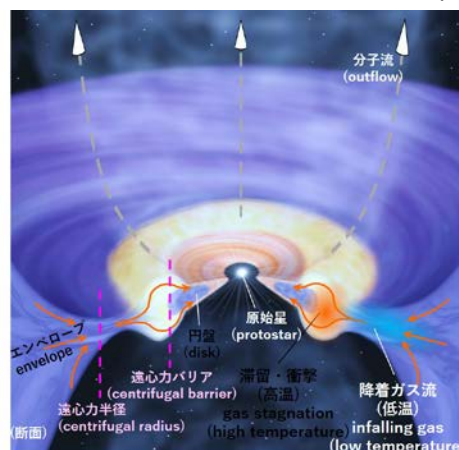
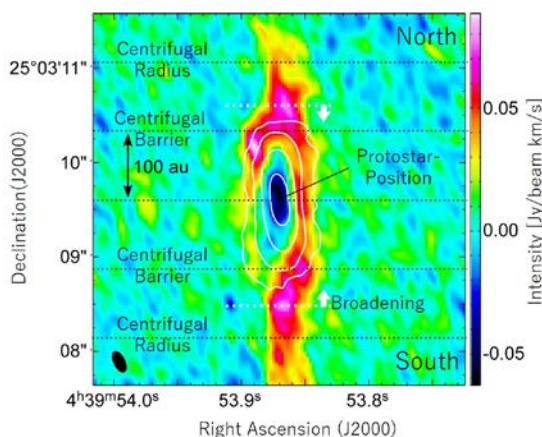


Fig. 7 (Left) Integrated intensity distribution of CCH ($N=4-3$, $J=9/2-5/2$, $F=5-4$ and $4-3$: colour) superposed on the 0.8 mm dust continuum map (contours: 10σ , 40σ , 160σ , 320σ and 640σ). The IRE traced by CCH is broadened inward of the radius of about 150 au. (Right) Illustration of envelope/disk-system image revealed by the ALMA observation.

8. Distribution of D₂CO in L1527 (Led by Yoshida)

We have analyzed ALMA observations of formaldehyde (H₂CO) and its deuterated species (D₂CO) towards a low-mass star-forming region L1527. We have found that the distribution of D₂CO is different from that of the normal species. H₂CO line emission is concentrated within 100 au around the protostar, whereas D₂CO line emission mainly comes from the outer envelope. The absence of high velocity components of D₂CO also supports that D₂CO is deficient in the vicinity of the protostar. By analyzing 2 lines of D₂CO and 1 line of H₂CO, the deuterium fractionation ratio is derived to be lower at the protostar position than that in the outer envelope. We have also analyzed the observations of CCH and CCD, and confirmed that the deuterated species is deficient at the protostar while the normal species resides in the inner infalling-rotating envelope around the protostar. These results indicate that the normal species are selectively produced in the vicinity of the protostar, while the deuterated species are destructed as they fall towards the protostar. Detailed observations and analysis are needed to investigate the formation mechanism of the normal species around the protostar.

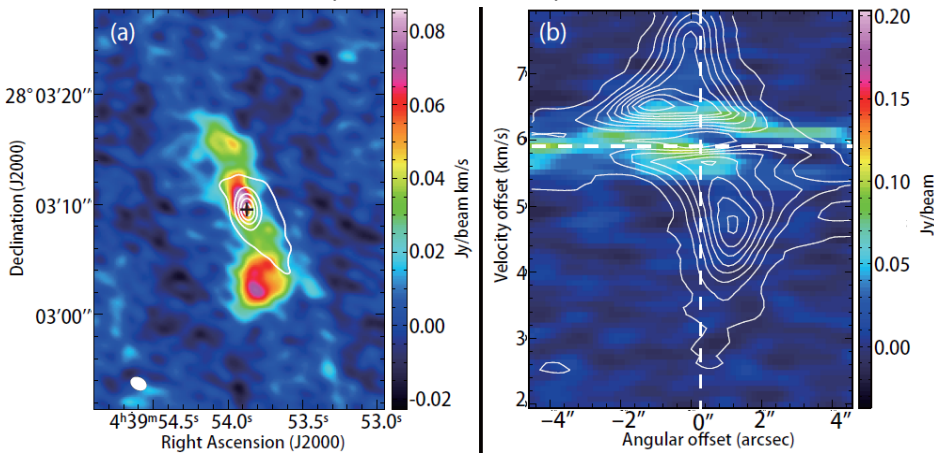
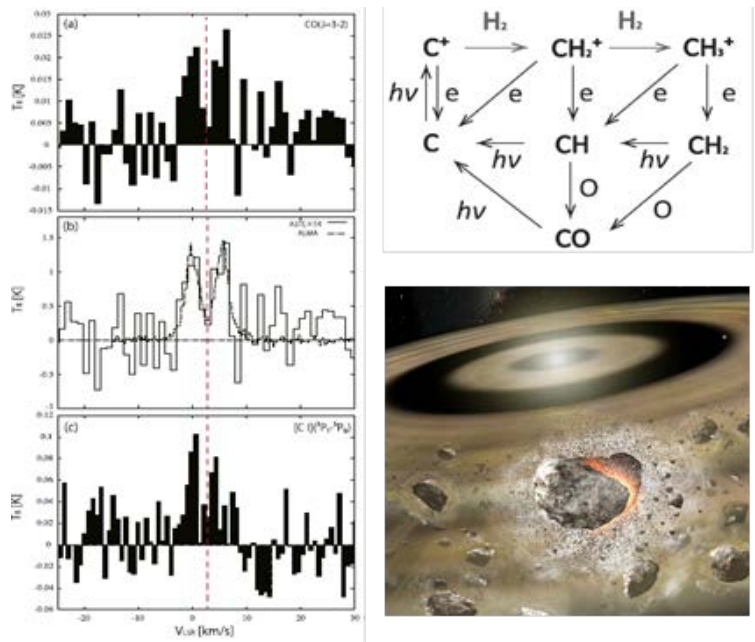


Fig 5. (a) Integrated intensity distribution of D₂CO (4₀₄-3₀₃; color) superposed on that of H₂CO (5₁₅-4₁₄; contours). (b) PV diagram of D₂CO (4₀₄-3₀₃; color) superposed on that of H₂CO (5₁₅-4₁₄; contours) along north-south direction.

9. Detection of [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris (Led by Higuchi)

We have detected [C I] $^3P_1-^3P_0$ emissions in the gaseous debris disks of 49 Ceti and β Pictoris with the 10 m telescope of the Atacama Submillimeter Telescope Experiment, which is the first detection of such emissions. The line profiles of [C I] are found to resemble those of CO($J = 3-2$) observed with the same telescope and the Atacama Large Millimeter/submillimeter Array. This result suggests that atomic carbon (C) coexists with CO in the debris disks and is likely formed by the photodissociation of CO. Assuming an optically thin [C I] emission with the excitation temperature ranging from 30 to 100 K, the column density of C is evaluated to be $(2.2 \pm 0.2) \times 10^{17}$ and $(2.5 \pm 0.7) \times 10^{16} \text{ cm}^{-2}$ for 49 Ceti and β Pictoris, respectively. The C/CO column density ratio is thus derived to be 54 ± 19 and 69 ± 42 for 49 Ceti and β Pictoris, respectively. These ratios are higher than those of molecular clouds and diffuse clouds by an order of magnitude. The unusually high ratios of C to CO are likely attributed to a lack of H₂ molecules needed to reproduce CO molecules efficiently from C. This result implies a small number of H₂ molecules in the gas disk, i.e., there is an appreciable contribution of secondary gas from dust grains. **Reference: #14** in the publication list

Fig.7 (Left) Detection of Submillimeter-wave [C I] Emission in Gaseous Debris Disks of 49 Ceti and β Pictoris (a) CO spectrum observed with the ASTE toward 49Ceti. (b) Comparison with the ALMA spectrum. (c) [C I] spectrum observed with the ASTE toward 49Ceti. The vertical red line indicates the systemic velocity of the gas disk (Dent et al. 2005). (Right top) Basic carbon chemistry producing CO in debris disks. (Right bottom) Artist's image of debris disk



10. A New Terahertz Emission Spectrometer (Led by Chiba)

In radio astronomy, accurate rest frequencies of molecular transitions are indispensable for secure identifications of molecular species and accurate analysis 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 THz emission spectrometer. This spectrometer is equipped with a superconducting hot electron bolometer (HEB) mixer receiver covering the frequency ranges of 0.8-0.9 THz and 1.3-1.5 THz, and XFFTS spectrometer with the spectral resolution of a few tens of kHz as a backend. The lower frequency measurements are also planned by using the ALMA-type SIS mixer receivers.

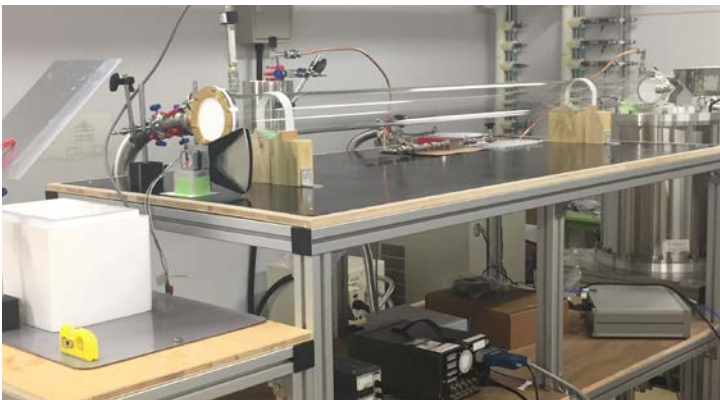


Fig.9 Gas-cell and THz-HEB-receiver system

Oral Presentations

Invited

- 1) Nami Sakai, Star Formation in Different Environments, "Chemical diagnostics of disk formation", **2016**, Jul. 25-29, ICISE, Quy Nhon, Vietnam
- 2) Aya Higuchi, ALMA ワークショップ: デブリ円盤から太陽系へ, ALMA 望遠鏡によるデブリ円盤観測, 千葉工業大学 東京スカイツリーキャンパス, 2016 年 8 月 8-9 日
- 3) Nami Sakai, RIKEN summer school, "Astrochemical Approach to Star and Planet Formation", Tsukuba International Congress Center, Japan, 9-10, Sep., 2016
- 4) Nami Sakai, Pioneering New Fields: Forefront of RIKEN's Science and Beyond, "Astrochemistry: A Growing Interdisciplinary Field", **2016**, Nov. 21-22, Japan
- 5) 樋口あや, 宇宙電波懇談会, "研究(星団・惑星形成)・評価活動(45m・ALMA)・教育経験を振り返って", 国立天文台, 三鷹, 2017 年 2 月 22-23 日
- 6) Nami Sakai, ESO Star Formation conference: Star Formation from Cores to Clusters, "Observation Overview: Pre- and Protostellar Cores", **2017**, Mar. 5-9, Santiago, Chile
- 7) Satoshi Yamamoto, Yoko Oya, and Nami Sakai, IAU symposium 332: Astrochemistry VII, "Chemical Tracers of Dynamics in Low-Mass Protostellar Objects", 20-24, March, 2017, Puerto Varas, Chile. (A proceeding paper is submitted)

Contributed

- 1) 坂井南美, 樋口あや, 大屋瑤子, 渡邊祥正, 山本智, Cecilia Ceccarelli, Bertrand Lefloch, 花輪知幸, 廣田朋也, 相川祐理, 酒井剛, "Vertical Structure of the Transition Zone from Infalling Rotating Envelope to Disk in the Class 0 Protostar, IRAS04368+2557", P122a, 日本天文学会, 愛媛大学, 2016 年 9 月 14-16 日
- 2) 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 H₂CO の重水素化物の観測", P118a, 日本天文学会, 愛媛大学, 2016 年 9 月 14-16 日
- 3) Nami Sakai, "Tracing the production pathways of molecules by ¹²C/¹³C ratio", Fractionation of isotopes in space, Florence, Italy, 10-13, Oct., 2016
- 4) Kento Yoshida, "Molecular isotopic ratios in the low-mass protostar L1527", Fractionation of isotopes in space, Florence, Italy, 10-13, Oct., 2016
- 5) Aya Higuchi, "CO survey towards debris disks with ALMA/APEX", Workshop on Interstellar Matter 2016, Institute of Low Temperature Science, Hokkaido University, Japan, Oct.19-Oct.21, 2016
- 6) 坂井南美, 樋口あや, 大屋瑤子, 渡邊祥正, 山本智, Cecilia Ceccarelli, Bertrand Lefloch, 花輪知幸, 廣田朋也, 相川祐理, 酒井剛, "Resolving Envelope to Disk Transition around the Class 0 Protostar, IRAS04368+2557", P138a, 日本天文学会, 九州大学, 2017 年 3 月 15-18 日
- 7) Yichen Zhang, ESO Star Formation conference: Star Formation from Cores to Clusters, "outflow Entrainment and Feedback: A Case Study with HH46/47 Molecular Outflow", **2017**, Mar. 5-9, Santiago, Chile

Posters

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