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東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

Press Release

"A Drastic Chemical Change Occurring in Birth of Planetary System: Has the Solar System also Experienced it?

1. Date and Time: 14:00 – 15:00 of February 10, 2014 (JST)

2. Place: Faculty of Science Bldg. 1, Rm 233.

3. Presenters : Nami Sakai, Assistant Professor, Department of Physics, Graduate School of Science, The University of Tokyo

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4. Key Points

Background: A new star and its planetary system are formed through gravitational collapse of interstellar gas and dust. It has so far been believed that interstellar matter is smoothly brought into a gas disk forming a planetary system as it is.

Result: A drastic chemical change associated with formation of the disk around a young protostar has been discovered with ALMA. Infalling gas is jammed up due to centrifugal force around the outer edge of the disk, where local heating causes a drastic chemical change.

Outlook: The Solar system may also have experienced it. It is very interesting to explore how the observed phenomenon is general in planetary system formation, and also how it affected the pre-solar materials found in meteorites.

5. Abstract:

A star is formed by gravitational contraction of interstellar gas (mostly H_2) and dust. Even after the birth of a protostar (a baby star), the gas and dust in the envelope are still infalling onto the protostar. At the same time, the gas disk is grown up around the protostar, and is eventually evolved into a planetary system. However, formation processes of the gas disk as well as the associated chemical changes are left unexplored observationally. Dr. Nami Sakai, assistant professor of physics in the University of Tokyo, and her global team observed the young protostar L1527 in the Taurus molecular cloud at a high spatial resolution with ALMA, and discovered an unexpected chemical change in the transition zone between the infalling envelope and the gas disk. So far, it has been believed that interstellar matter is smoothly delivered to the gas disk around the protostar without any significant chemical changes. However, it is now found to be oversimplified. The infalling gas is jammed up due to centrifugal force at the outer edge of the gas disk, where local heating causes a drastic chemical change. This chemical change highlights the outer edge of the gas disk which is still growing. The Solar system may also have experienced this situation. It is necessary to assess how pre-solar materials found in meteorites are affected by such a chemical change during the solar-nebula formation. In this sense, this

study raises an important problem in understanding how the environment of the Solar system is general or miracle in the Universe.

6. Contents

6.1 Background

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 (protoplanetary disk), whose size is an order of 100 AU, 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 is eventually born in the Earth. How unique is the situation happened for the Solar system in the Universe? In order to answer this question, understanding formation of protoplanetary disks as well as the associated chemical evolution in various star forming regions is essential. Toward this goal, extensive observational efforts have been done. So far, most of them have focused on a change in the physical structure and kinematics during the formation process. However, it was very difficult to distinguish the protoplanetary disk from the infalling envelope clearly with such conventional approaches. On the other hand, the chemical evolution associated with the disk formation has scarcely been studied observationally because of insufficient sensitivity and spatial resolution of the previous radio telescopes. As a result, a chemical model calculation under many assumptions is an only approach for it. Naturally, the physical and chemical changes in the disk formation should be coupled with each other. From a novel point of view looking at physics and chemistry simultaneously, the disk formation around a young protostar has been explored.

6.2 Result

L1527 in the Taurus molecular cloud is a molecular cloud core [1] which harbors a young protostar. A global team led by Dr. Nami Sakai, assistant professor of Department of Physics, the University of Tokyo, conducted high-sensitivity high-spatial-resolution observations of L1527 with ALMA (Atacama Large Millimeter/submillimeter Array) [2] newly constructed in the Atacama desert in Chile, and investigated the formation process of the disk formation in spectral lines of several molecules [3].

As a result, Sakai et al. have found that carbon-chain molecules [4] and their related species such as cyclic-C_3H_2 almost completely disappear in the gas phase inward of the radius of 100 AU from the protostar (Figure 1, top left; top right). The motion of the gas is investigated on the basis of the precise measurement of the Doppler shift of their spectral lines, and it is revealed that the radius of 100 AU corresponds to the radius of the centrifugal barrier [5] (Figure 2). At this radius, infalling gas is jammed up due to the centrifugal force, and is gradually transferred to the inner disk. Namely, this is the front of the disk forming region. It has clearly been identified with the spectral line of cyclic-C_3H_2.

On the other hand, the distribution of sulfur monoxide molecules (SO) is found to be localized in a ring structure located at the radius of the centrifugal barrier (100 AU) (Figure 1, bottom left; bottom right). Furthermore, the temperature of the SO molecules is found to be higher than that of the infalling gas. This means that the infalling gas probably causes weak shock when it inrushes into the outer edge of the disk around the centrifugal barrier.

The gas temperature is raised around this radius, and the SO molecules frozen on dust grains are liberated into the gas phase. Hence, the spectral lines of SO also highlight the disk-formation front. Since the density of the disk is 10^8 cm^{-3} or higher, most of molecules are frozen out onto dust grains in the disk after they pass through the front.

It is not anticipated at all that such a drastic chemical change occurs in the transition zone between the infalling envelope and the inner disk. The disk formation and the associated chemical change have successfully been detected by observations of the two chemical species, cyclic-C_3H_2 molecule and SO molecule.

6.3 Outlook

This study has demonstrated a drastic change in chemical composition associated with the disk formation around the young protostar (cf; Figure 3). With a coupled view of physics and chemistry, it has also succeeded in highlighting the outermost part of the disk where the gas is still accreting. This success is realized by high-sensitivity and high-spatial-resolution observations with ALMA, and such a study will be extended toward various star-forming regions. In particular, it is very interesting to examine how widely the above picture seen in L1527 is applicable to other star-forming regions. Although many observational efforts aiming at understandings of planetary-system formation have been made, this study is novel in focusing on the chemical change. By extending this new method to various solar-type protostars, diversity and generality of the chemical evolution from interstellar matter to planetary matter will be unveiled within the next few years with ALMA. Then, we can critically examine whether the Solar system experienced this drastic chemical change. In parallel to the astronomical approach, the origin of the Solar system is being investigated by exploring the Solar system itself through microanalyses of meteorites, spectroscopy of comets, sample return from the asteroids, and so on. The present study will also give a strong impact on these studies in tracing their origin back to interstellar clouds.

7. Journal:

Journal: Nature
Title: Change in the chemical composition of infalling gas forming a disk around a protostar

Authors: Nami Sakai, Takeshi Sakai, Tomoya Hirota, Yoshimasa Watanabe, Cecilia Ceccarelli, Claudine Kahane, Sandrine Bottinelli, Emmanuel Caux, Karine Demyk, Charlotte Vastel, Audrey Coutens, Vianney Taquet, Nagayoshi Ohashi, Shigehisa Takakuwa, Hsi-Wei Yen, Yuri Aikawa & Satoshi Yamamoto

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8. Important Notice: Must follow the regulation for the press release of Nature. The paper will be online on 13 February 3:00 JST (12 February 18:00 London Time).

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10: Notes for the contents.

[1] Molecular Cloud Core : A dense part of a molecular cloud, whose H_2 density is higher than 10^4 cm-3. It is gravitationally bound, and is a birth place of a new star. A typical size is 0.3 light years and a typical mass is 10 times the solar mass.

[2] ALMA : ALMA (Atacama Large Millimeter/submillimeter Array) is a gigantic radio interferometer array with 66 parabola antennas (Figure 4). ALMA consists of fifty 12-m antennas and "Atacama Compact Array (ACA)" which is composed of four 12-m antennas and twelve 7-m antennas. By spreading these transportable antennas over the distance of up to 18.5 km, ALMA achieves the resolution equivalent to a telescope of 18.5 km in diameter, as a telescope with the world's highest sensitivities and resolutions at millimeter and submillimeter wavelengths.

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Southern Observatory (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.

[3] Spectral Line : In this document, it means 'rotational spectral line', which is caused by the change in rotational energy levels by emitting or absorbing the electromagnetic radiation in the radio wavelength (millimeter- and submillimeter-wave regions). The rotational motion of a molecule is described by quantum mechanics, and has descrete energy levels. Frequencies of the rotational spectral lines of molecules are different from molecular species to molecular species, and we can definitively identify molecular species from observed spectral lines. The abundance of molecules as well as the H_2 density and the temperature where the molecules reside can be derived from the observed intensity.

[4] Carbon-Chain Molecules : A group of molecular species in which carbon atoms have a linear configuration. Several series of carbon-chain molecules such as HC_nN, C_nH, C_nH_2, C_nS, and C_nO are known as interstellar molecules. These are highly 'unsaturated' molecule having many mutiple bonds (double or triple bonds), and are chemically reactive in general. They are scarcely found in the terestrial conditions (density of 10^{19} cm^{-3} and the temperature of 300 K), but are known to be abundant in interstellar clouds under the extreme physical condition (H_2 density of 10^4-10^7 cm^{-3} and the temperature of 10-100 K). Its life time in interstellar clouds is typically a few times 10^5 years. In addition to the linear form, the isomers having a cyclic structure are also known. An example is cyclic C_3H_2.

[5] Centrifugal Barrier : When an infalling particle with conservation of its angular momentum is considered, the particle cannot go inward of the certain radius due to the centrifugal force. This is called as the centrifugal barrier, where the all kinetic energy is converted to the rotational energy. This is just a half of the centrifugal radius, where the centrifugal force and the gravitational force are balanced. The infalling gas is jammed up around the centrifugal barrier, and then a part of it will gradually be delivered into the inner disk by loosing the angular momentum.

11. Figures:

All the figures presented here can be taken from the following web sites.
http://www.resceu.s.u-tokyo.ac.jp/~submm/member/nami/PressRelease/f1_almadata_en.jpg
http://www.resceu.s.u-tokyo.ac.jp/~submm/member/nami/PressRelease/f2_model_en.jpg
http://www.resceu.s.u-tokyo.ac.jp/~submm/member/nami/PressRelease/f3_image.jpg
http://www.resceu.s.u-tokyo.ac.jp/~submm/member/nami/PressRelease/f4_alma.jpg

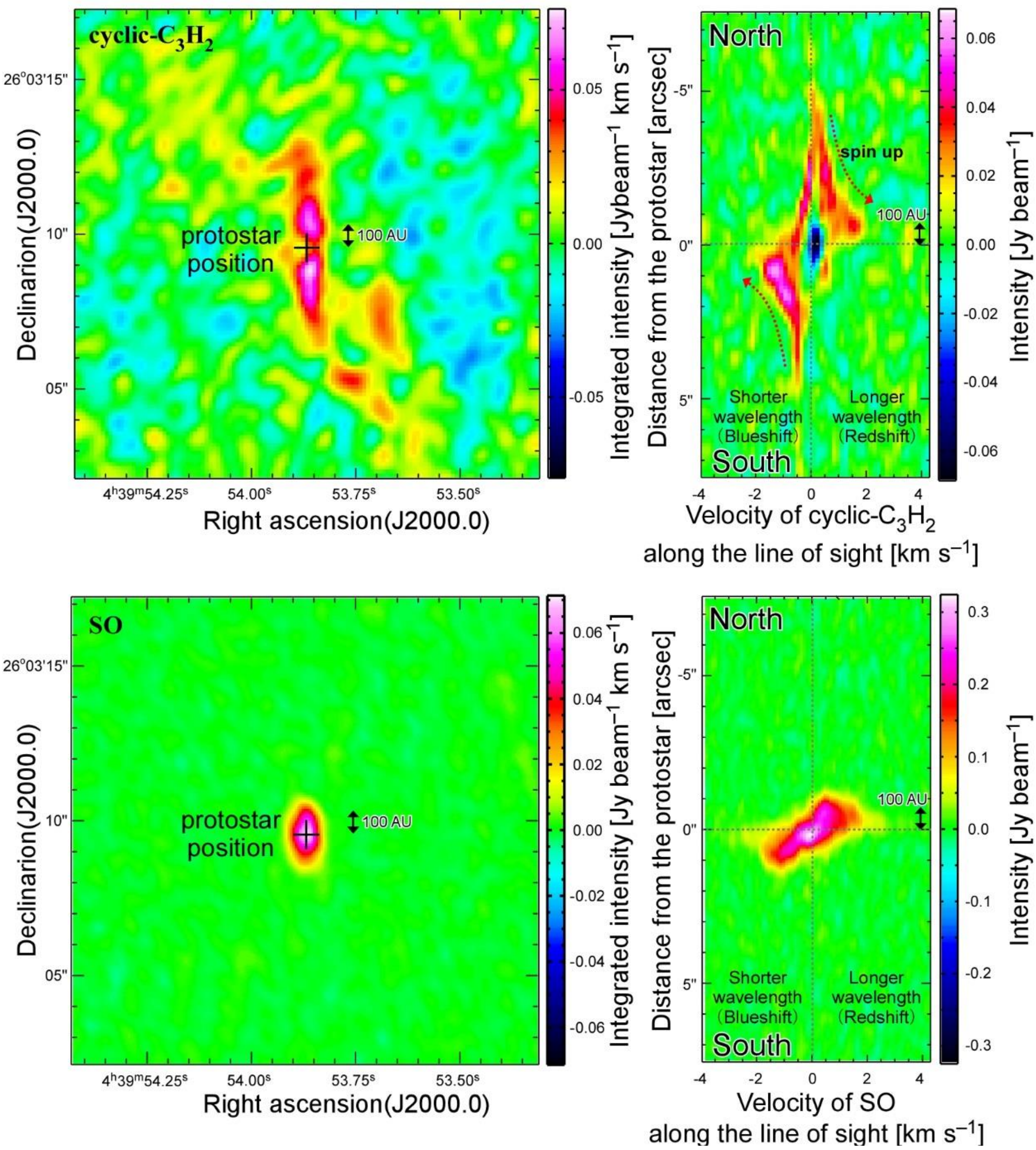

Figure 1. (top left) : Integrated intensity distribution of the cyclic-C_3H_2 (5_{23}-4_{32}) line observed with ALMA. **(top right) :** The position velocity diagram of the cyclic-C_3H_2 (5_{23}-4_{32}) line along a north-south line passing through the protostar position. Frequency of the spectral line is shifted toward red (longer wavelength) and blue (shorter wavelength) when the molecule is moving away from us and moving toward us, respectively, due to the Doppler effect. Thus, the velocity can be measured by the frequency shift accurately, which is plotted in the diagram. The cyclic-C_3H_2 line is shifted to red in the north part of the protostar, whereas to blue in the south part. This means that we are looking at the rotating envelope from the edge-on direction. **(bottom left) :** Integrated intensity distribution of the SO (J_N=7_8-6_7) line. The SO distribution seems to fill up the dip of the cyclic-C_3H_2 distribution. **(bottom right) :** The position velocity diagram of the SO (J_N=7_8-6_7) line along a north-south line passing through the protostar position. The velocity is proportional to the position offset from the protostar. This means that SO comes from a rotating ring with a cirtain radius as explained in Figure 2.

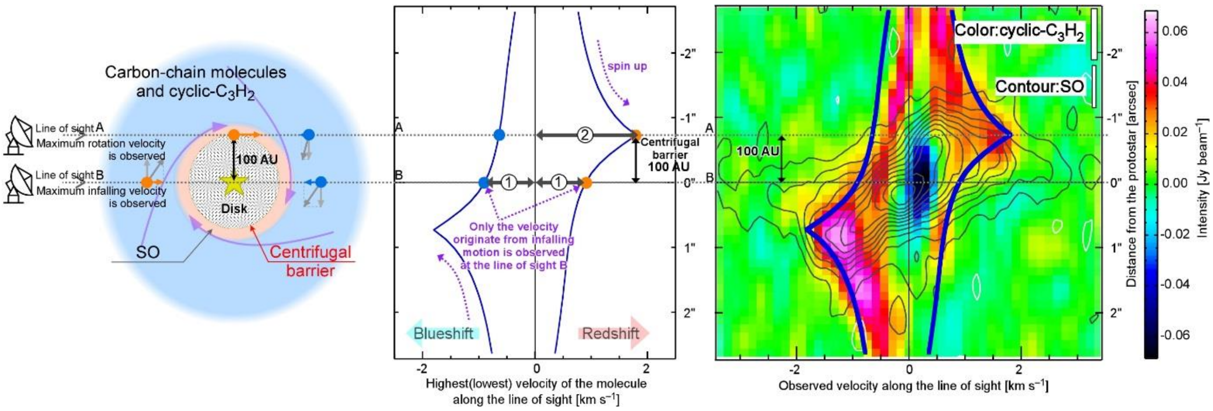

Figure 2. : (left) Schematic illustration of the infalling-rotating envelope around the protostar. The gas can not go inside the centrifugal barrier due to the centrifugal force. The observer is on the left-hand side, looking at the envelope in an edge-on configuration **(middle) :** The highest and lowest velocities of the infalling-rotating gas calculated from the model. The emissions of the colored closed circles come from the corresponding colored closed circles in the left panel. **(right) :** The highest and lowest velocities shown in the middle panel are superposed on the position-velocity diagram of cyclic-C_3H_2. The observation of cyclic-C_3H_2 showes a beautifull agreement with the model. The cyclic-C_3H_2 molecules completely disappear at a radius of ~100 AU (the centrifugal barrier) from the protostar, whereas SO appears at the radius. SO preferentially exists in the ring whose radius is that of the centrifugal barrier.

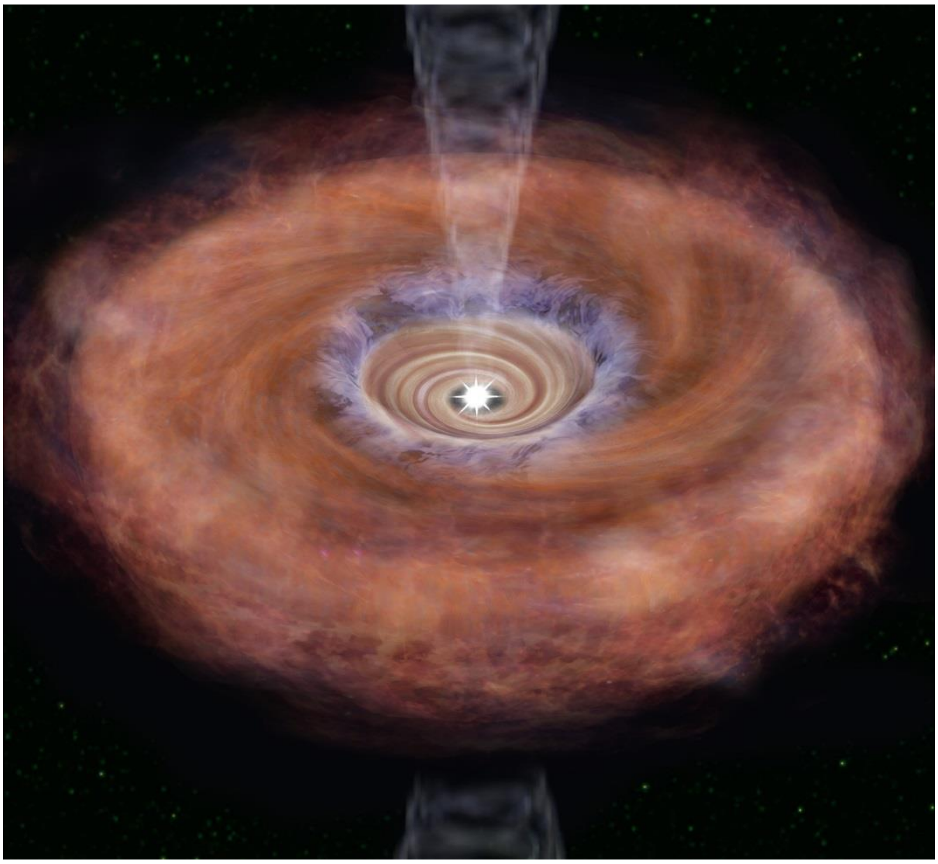

Figure 3. Illustration of rotating-infalling gas toward a protostar. The centrifugal barrier is highlighted by the molecular line emission of sulfermonooxcyde(colored blue). Inside the barrier, a protostellar disk is being formed.

Figure 4. Atacama Large Millimeter/submillimeter Array (ALMA).