# Mysterious Interstellar Icy Objects
## — A New Site for Organic Molecule Formation? —


## Abstract
Like snow forming in clouds on a freezing winter day, interstellar ices form in specific regions of the galaxy. Astronomers from Niigata University and The University of Tokyo (Japan) conducted molecular gas observations of two enigmatic interstellar objects using the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. These objects were previously discovered by the Japanese infrared satellite AKARI and are known to be rich in interstellar ices containing water and organic molecules, though their properties remained unclear. The ALMA observations have revealed the distance, motion, size, and chemical composition of the molecular gas associated with these objects. However, their characteristics do not match those of any previously known interstellar objects where ices have been detected. This study suggests that these two objects may represent a new class of interstellar icy objects that provide an environment conducive to the formation of ices and organic molecules. The findings were published in *The Astrophysical Journal* on February 25, 2025.


## Background
Organic molecules that serve as the building blocks of life are believed to form in space, but their exact formation sites and delivery mechanisms to planets remain a major mystery in astronomy and planetary science. One of the key elements in solving this mystery is the presence of ice in interstellar environments. The interstellar medium contains submicron-sized solid particles, known as interstellar dust, composed mainly of carbon, oxygen, silicon, magnesium, and iron. In cold, dense, and shielded regions of the galaxy, atoms and molecules adhere to the surfaces of these dust particles, leading to the formation of interstellar ices. This process is similar to how snow forms in Earth's clouds. Since chemical reactions in solid states are far more efficient at producing complex organic molecules than those in gaseous states, interstellar ices are believed to be a crucial site for such molecular formation.

In 2021, using data from the infrared satellite AKARI, astronomers discovered two interstellar objects that are bright in near- to mid-infrared wavelengths. These objects, located in the Galactic plane toward the Scutum-Centaurus Arm, exhibit deep absorption bands caused by ices and dust. Spectral analysis suggested that the ices contain water, carbon dioxide, carbon monoxide, and organic molecules such as methanol (Fig.1 right). Typically, interstellar ices are detected in dense regions of star-forming clouds, but these two objects do not belong to any known star-forming regions. This discovery raised questions about their nature.

## Research Overview and Results

To investigate the properties of these mysterious interstellar icy objects, the research team used the ALMA telescope to observe them at a wavelength of approximately 0.9 mm. While infrared observations are effective for studying solid materials, radio observations are more useful for analyzing the motion and composition of associated gases. If these two interstellar objects were forming stars, ALMA's high spatial resolution and sensitivity would detect various molecular emissions. Additionally, if a previously undetected molecular cloud were present in the direction of these objects, it would appear as spatially extended gas emissions in carbon monoxide.

However, the observations revealed something different from either of these expectations. At the positions of the two icy objects, only molecular emission lines of carbon monoxide and silicon monoxide were detected, exhibiting a very compact distribution of less than one arcsecond (Figure 1, left). On the one hand, the submillimeter thermal emission from interstellar dust, which was expected to be detected in objects deeply embedded in interstellar dust like these two, was not detected. Through these ALMA observations, various physical and chemical properties of the mysterious icy objects have been revealed.

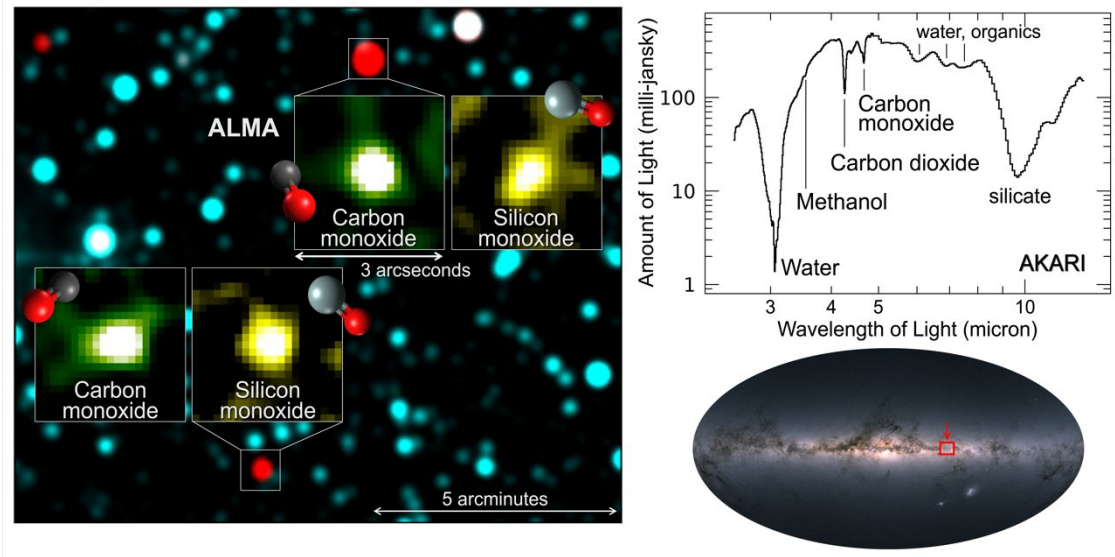


Figure 1. Left: Molecular emission lines from mysterious icy objects captured by the ALMA telescope. The background image is an infrared composite color map, where 1.2-micron light is shown in cyan and 4.5-micron light is in red, based on infrared data from 2MASS and WISE. Top right: Infrared spectrum of the upper icy object in the left image, observed by the AKARI satellite, showing absorption bands due to ices and dust. Bottom right: The location of the two icy objects in the Galactic plane (image modified from the GAIA data). Credit: ALMA (ESO/NAOJ/NRAO), ESA/Gaia/DPAC, T. Shimonishi et al. (Niigata Univ.).

First, based on the kinematic distances estimated from the line-of-sight velocity of the gas, it was suggested that the two objects are located approximately 30,000 to 40,000 light-years away from Earth. Additionally, the significant difference in their velocities indicates that these objects are kinematically independent and situated at different distances. "*This was an unexpected result, as these peculiar objects are separated by only about 3 arcminutes on the celestial sphere and exhibit similar colors, brightness, and interstellar ice features*, but they are not linked each other," says Takashi Shimonishi, an astronomer at Niigata University, Japan, and the lead author of the paper.

Understanding the wavelength range in which an object emits radiation most strongly is useful for investigating its physical properties. Interstellar objects known to be associated with ices are embedded in large amounts of interstellar dust, causing them to shine brightly in the far-infrared to submillimeter wavelength range. However, as shown in Figure 2, the ALMA observations in this study did not detect submillimeter radiation from the two icy objects, revealing an unusual energy distribution that does not match the characteristics of previously known interstellar icy objects.

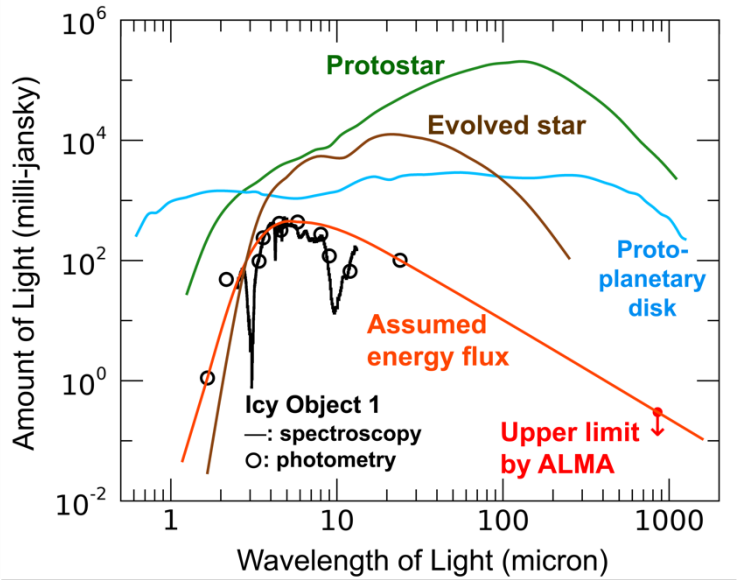


Figure 2. Energy distribution of one of the mysterious icy objects (black) compared with those of known interstellar icy objects. Interstellar ices are detected in protostars (green), young stars with protoplanetary disks (cyan), and mass-losing evolved stars (brown), but the spectral characteristics of the mysterious icy object do not match any of these known sources.
Credit: T. Shimonishi et al. (Niigata Univ.)

The molecular composition of the gas surrounding these celestial bodies was also analyzed. The ratio of silicon monoxide to carbon monoxide was found to be unusually high, suggesting the presence of strong shock waves that have disrupted interstellar dust. The detection of broad molecular emission lines further indicates that these objects are associated with turbulent energy sources.

The molecular composition of the gas associated with the two objects was also analyzed. The molecular abundance ratio of silicon monoxide to carbon monoxide, estimated from the emission lines, was about 0.001, which is much higher than what is typically observed in normal molecular clouds. Regions where such abundant silicon monoxide is detected are limited to areas where interstellar dust is being destroyed by intense shock waves. Along with the detection of broad molecular emission lines from the two objects, which indicate that the gas is in vigorous motion, it is suggested that there is some energy source associated with the objects that is strongly disturbing the gas.

Observations also provided insights into their size. The team estimated the size of the gas and dust clouds associated with the two objects by comparing ALMA's emission data with AKARI's absorption data for gas, ice, and dust. As a result, it was found that the two objects are compact, ranging from 100 to 1,000 astronomical units in size, which is much smaller compared to typical molecular clouds or cores.

The unique properties of the mysterious icy objects revealed by the ALMA observations cannot be explained by the characteristics of any known objects associated with interstellar ices, such as newly formed stars, young stars with protoplanetary disks, evolved stars that exhibit intense mass loss, or bright stars located behind the dense molecular clouds. "*I have been studying interstellar ices for nearly 18 years, but these two objects puzzle me because they are unlike any other known source of interstellar ices*," says Takashi Shimonishi. "*They may represent a new class of interstellar objects that provide an environment conducive to the formation of ices and organic molecules*".

## Future Prospects

Compact and isolated interstellar objects that are surrounded by ices and dust, possess an environment conducive to the formation of complex organic molecules, are accompanied by a vigorous energy source that disturbs the gas, and shine brightly only in the near- and mid-infrared. Their true nature remains unknown at this time. "*Future high-resolution observations of the associated gas using the ALMA telescope, along with more detailed studies of ices and dust with the James Webb Space Telescope, would shed light on the nature of these mysterious icy objects*," hopes Takashi Shimonishi.

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