Press Release

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National Astronomical Observatory of Japan
Keio University

# A Stray Black Hole that Swirls Gas Clouds

## ―More Reliable Evidence of an Intermediate-Mass Black Hole Lurking around the Center of the Milky Way―

The Atacama Large Millimeter/submillimeter Array (ALMA) captured details of a previously unknown structure of the peculiar molecular cloud located near the center of the Milky Way. Analysis of its motion revealed the existence of a black hole with a mass 30,000 times that of the Sun. This result shows that there is a possibility that many other similar black holes are hidden around the center of the Milky Way.

Many galaxies are known to have a supermassive black hole at their nucleus, but their formation process is regarded as one of the big mysteries of the universe. In theory, it is thought that intermediate-mass black holes, which have masses of about several hundred to 100,000 times that of the Sun, act as "seeds," which then merge and grow to form a supermassive black hole. However, even though there have been several reported cases of intermediate-mass black holes, no definitive evidence proving their existence has yet been obtained.

For this research, a team consisting of Shunya Takekawa, a project researcher at the National Astronomical Observatory of Japan's Nobeyama Radio Observatory, Professor Tomoharu Oka of the Keio University Faculty of Science and Technology, Department of Physics, and others, used ALMA to carry out a high resolution radio wave observation of a molecular gas cloud with an unusual velocity discovered about 20 light-years away from Sagittarius A*, the nucleus of the Milky Way. From this, it seemed that this molecular gas cloud was made up of multiple gas streams having orbital motions influenced by a strong pull of an "invisible gravitational source." Detailed kinematic analyses revealed that an enormous mass equivalent to 30,000 times that of the Sun was concentrated in a region much smaller than our Solar System. This strongly suggests that a heavy intermediate-mass black hole is drifting near the nucleus of the Milky Way. The findings of this research are extremely important not only because they lead to an explanation of the origins of supermassive black holes and an understanding of galactic evolution, but also because they lead to the possibility of opening new doors for the investigation of black holes.

The findings of this research were published in the January 20 issue of the American astrophysics journal, The Astrophysical Journal Letters.

## 1. Main Points of Research

- A detailed observation of a peculiar molecular cloud discovered in the vicinity of Sagittarius A*, the nucleus of the Milky Way, was carried out using ALMA(*1), and this was found to be a complex of multiple gas streams with orbital rotational motion (revolving).
- From the orbital analysis, it was concluded that an "invisible mass"—intermediate-mass black hole—amounting to about 30,000 times the mass of the Sun is hiding at its center of rotation.
- Strong evidence of the existence of an intermediate-mass black hole drifting around the center of the Milky Way was obtained and a new method to locate faint "stray black holes(*2)," which have been difficult to discover up to now, was presented.

## 2. Background of Research

The existence of 2 types of black holes have currently been confirmed. These are the light black holes with masses several times to several tens of times greater than the Sun (stellar-mass black holes) and supermassive black holes with masses ranging from a million to 10 billion times that of the Sun. A stellar-mass black hole is formed when a star that is more than 30 times heavier than the Sun burns out and dies in a supernova explosion when it can no longer support its own weight. In a way, it can be said to be the carcass of a star. Supermassive black holes are known to exist as nuclei at the center of many galaxies. The Milky Way, the galaxy in which we exist, is no exception, and at its nucleus, which is known as Sagittarius A* and is located at a distance of about 25,000 light-years away from our Solar System, a supermassive black hole with a mass 4 million times that of the Sun is known to be hidden. However, the origin of supermassive black holes has not yet been explained, and it is one of the big mysteries of the universe.

As the detection of gravitational waves (*3) in recent years has shown, black holes get bigger by merging with each other. They also grow by swallowing surrounding material. In other words, it can be reasoned that supermassive black holes are formed by black holes swallowing large amounts of surrounding material and repeatedly merging with other black holes. However, there have been several reports of the existence of black holes with a mass less than that of supermassive black holes but heavier than stellar-mass black holes. But the presence of these black holes with an in-between mass (having a mass of about 100 to 100,000 times that of the Sun), called "intermediate-mass black holes," has not yet been corroborated and is causing considerable controversy. In the black hole community, it can be said that intermediate-mass black holes are the missing link and key to explaining the origin of supermassive black holes, so their discovery holds great meaning in astronomy.

## 3. Research Results

The research team discovered a small peculiar molecular cloud, HCN–0.009–0.044, located about 20 light-years away from "Sagittarius A*," the nucleus of the Milky Way, from observations carried out in 2016 using the East Asian Observatory's James Clerk Maxwell Telescope (JCMT). In general, molecular clouds move around the nucleus broadly in accordance with the galactic rotation, but this molecular cloud, HCN–0.009–0.044, showed odd behavior as it seemingly moved in the opposite direction to the gravitational rotation. From this motion in an unnatural direction, for which acceleration seemed to be created locally, the research team had pointed out the possibility that HCN–0.009–0.044 could be a result of a gravitational interaction between a faint "stray black hole(*2)" hidden there and the molecular gases.

For this research, the team conducted a high resolution submillimeter band spectral line observations using ALMA with the aim of uncovering the identity of HCN–0.009–0.044. As a result, the detailed structure and internal motion of HCN–0.009–0.044, which had been unclear until now, was revealed (figure 1). When it was discovered using the JCMT, it was considered to be one small molecular cloud (figure 1(a)), but from ALMA, it was shown that it in fact consists of multiple structures (figure 1(b)). There is a structure shaped like a balloon at the center of the figure (balloon), and to the left, a slender structure extending from north to south (stream) can be seen. The state of motion of these structures can be estimated from the velocity in the direction of the line of sight (line-of-sight velocity) obtained from the changes in frequency due to the Doppler effect. Figure 1 (c) shows the line-of-sight velocity at each location in color. It can be seen from this figure that there is a continuous change in velocity for each of the structures: clockwise from the northern side to the south in the case of the balloon, and in the case of the stream, as it curves slightly from the southern side to the north. These patterns indicating changes in velocity are typical of astronomical objects in orbital rotational motion. Furthermore, for orbital rotational motion to occur, a "gravitational force" is required. In other words, the motions of the balloon and stream strongly suggest the existence of an "invisible gravitational source."

In addition, the research team determined the three-dimensional orbits of the balloon and the stream based on observational data, and succeeded in calculating the mass of the gravitational source that causes these orbital motions. From the analysis, it was found that the balloon and the stream are moving along two different elliptical orbits centered on a common gravitational source, and that the mass of the gravitational source is about 30,000 times that of the Sun (figure 2). The minimum distance between the balloon's orbit and the gravitational source is about 0.2 light-years. In other words, this means that an enormous mass that is as much as 30,000 times greater than that of the Sun is packed into an area much smaller than 0.2 light-years. It is only natural to consider an astronomical object with such an exceptionally large mass density to be a black hole. Furthermore, no bright astronomical objects were detected in the same direction, and it is difficult to think, for example, that an ultra-dense star cluster is the gravitational source. Therefore, it can be concluded that an "intermediate-mass black hole" with a mass that is 30,000 times that of the Sun is hidden inside HCN–0.009–0.044.

Unlike previous observational results, this result was obtained upon a detailed understanding of the motions of the gas cloud around the black hole. It may therefore be said that more reliable evidence of an intermediate black hole has been acquired.

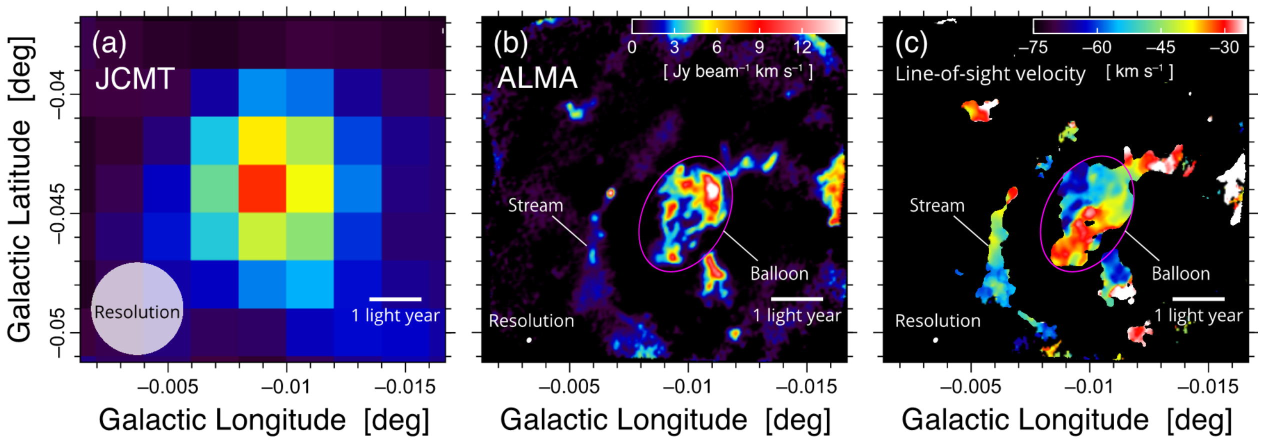


Figure 1

(a) Hydrogen cyanide (HCN) 354.6 GHz spectral line intensity map of the peculiar molecular cloud HCN–0.009–0.044 observed through the JCMT. The resolution is insufficient to depict cloud spread and it looks like a single structure.

(b) The same spectral line intensity map observed through ALMA. The internal structure of HCN–0.009–0.044 is seen in great detail.

(c) Line-of-sight velocity distribution map. The systematic line-of-sight velocity of HCN–0.009–0.044 is about 50 km/s (yellow-green). Velocities moving away are indicated by the colors on the red side, while approaching velocities are shown by the colors on the blue side of the spectrum.

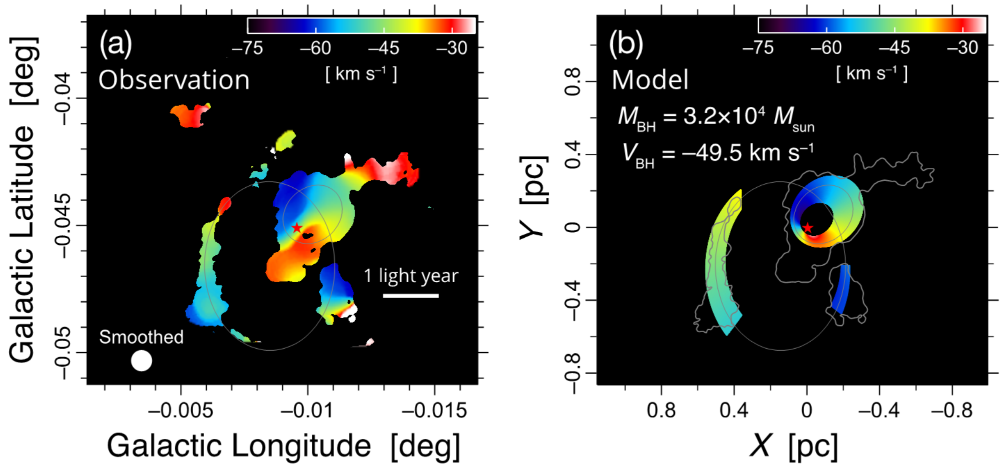


Figure 2

(a) Observed line-of-sight velocity distribution map. However, to reduce the effects of noise during analysis, it was created using smoothed data (the data used for figure 1(c) was not smoothed).

(b) Line-of-sight velocity distribution map modelled based on the balloon and stream position-velocity data. A very good reproduction of the observation results (a) is seen. The 2 ellipses indicate the orbital motion of the balloon and stream, and the red star indicates the location of the black hole. The mass and line-of-sight velocity of the black hole obtained as the optimal value for the model is $(3.2\pm0.6)\times10^4$ solar mass and $-49.5^{+1.0}_{-0.7}$ km/s respectively.

## 4. Significance of Research Results

This research succeeded in detecting the distinct orbital motions of the gas cloud surrounding the "invisible mass," and calculated its mass to be about 30,000 times that of the Sun, thereby presenting more reliable evidence toward the existence of intermediate-mass black holes. The outcomes of this research have great significance for the following 2 reasons. The first is that an intermediate-mass black hole was discovered in the vicinity (at a distance of about 20 light-years away) of Sagittarius A*, the nucleus of the Milky Way. In the future, there is a possibility that this intermediate-mass black hole will be swallowed by the supermassive black hole at the nucleus and contribute to its growth. Intermediate-mass black holes are key to explaining the origins of supermassive black holes and understanding galactic evolution, so the discovery itself has great meaning.

The other significance is that the black hole discovered in the course of this study is "faint." Dozens of black holes have been detected in the Milky Way to date, but most of these had been black hole binary star systems with a secondary star (*4) and a brightly shining accretion disk. According to theoretical predictions, there are at least 100 million black holes in the Milky Way, including large and small ones. In other words, most of the black holes in the Milky Way are faint because not enough material is supplied to them by secondary stars, and for this reason, discovering them through the conventional method of detecting bright emissions from the accretion disk is difficult. However, as was done in this study, attempting to detect gas clouds being swung around by strong gravitational forces is an effective method to search for faint black holes. The research team has also discovered an intermediate-mass black hole candidate with a mass of 100,000 solar masses located about 200 light-years away from the nucleus of the Milky Way (Press Release, September, 2017). As was done in this research, by focusing on molecular gas clouds with unusual velocities, it is anticipated that many black hole candidates will start to be discovered one after the other. This pioneering series of studies could serve as a cornerstone for breaking new ground in the search for black holes.

5. Details of Original Paper

The findings of this research were published in the January 20 issue of the American astrophysics journal, The Astrophysical Journal Letters. The title of the paper, the authors, and their affiliation at the time the research was carried out are as follows:

"Indication of Another Intermediate-mass Black Hole in the Galactic Center"

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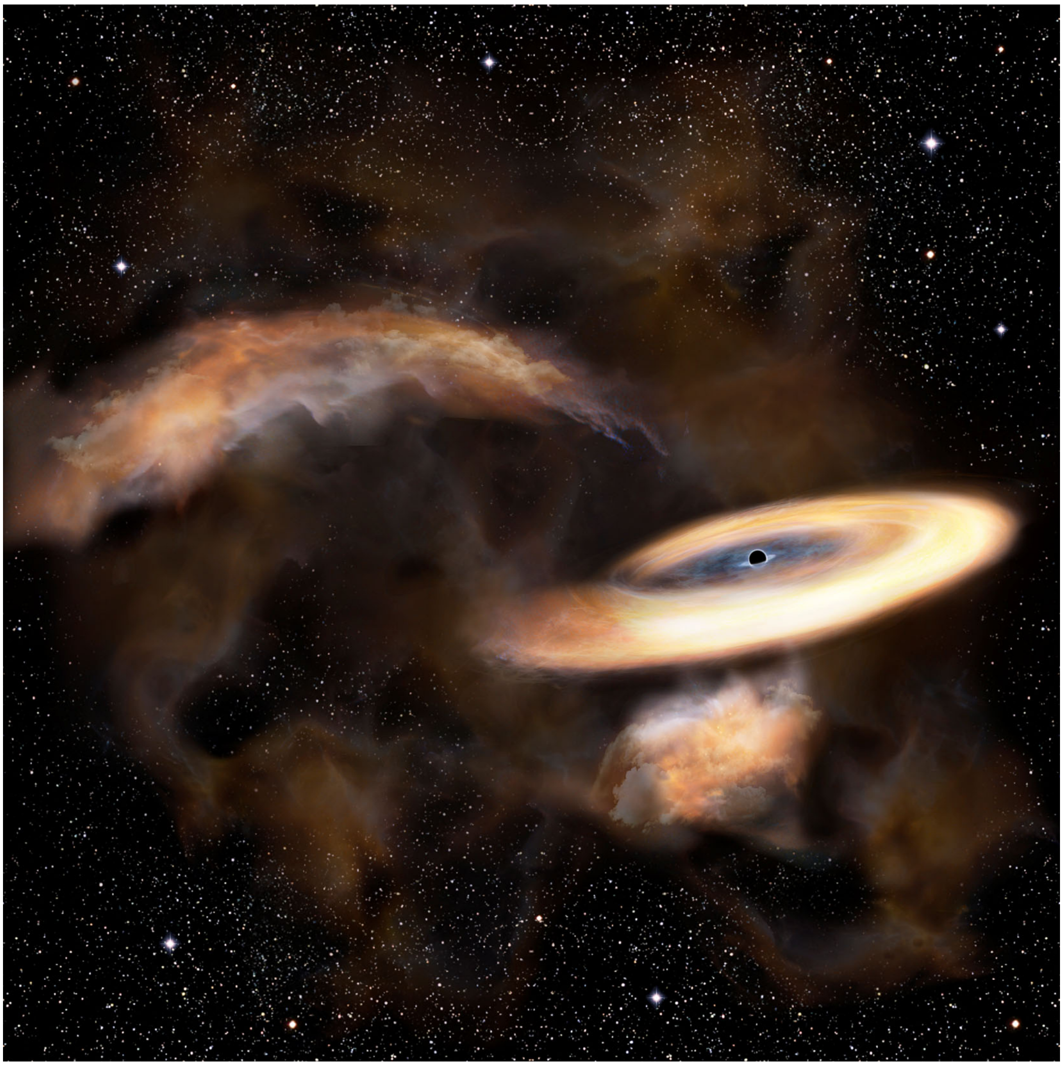

Figure 3: Artist's illustration of a gas cloud being swirled around by an intermediate-mass black hole

＜Related links＞
National Astronomical Observatory of Japan, Nobeyama Radio Observatory
https://www.nro.nao.ac.jp
Atacama Large Millimeter/submillimeter Array (ALMA)
https://alma-telescope.jp
Keio University Faculty of Science and Technology, Tomoharu Oka Laboratory
http://aysheaia.phys.keio.ac.jp/index.html

＜Announcements of Related Research＞

・ National Astronomical Observatory of Japan and Keio University Press Release (September , 2017)
  First Detection of an Intermediate-mass Black Hole Candidate in the Milky Way
  https://www.nao.ac.jp/en/news/science/2017/20170928-alma.html
  https://www.keio.ac.jp/en/press-releases/2017/Sep/27/49-24314/

＜Glossary＞

*1 ALMA telescope: A giant radio telescope located at a height of about 5,000 meters above sea level in the Atacama Desert, Chile. It is a joint international project that includes the European Southern Observatory representing Europe, National Radio Astronomy Observatory representing North America, and National Astronomical Observatory of Japan representing East Asia.

*2 Stray black hole: Material falling into a black hole form a structure called an accretion disk around the black hole. Generally, the accretion disk is heated and emits light, and the greater the amount of material that is deposited in the accretion disk, the brighter it glows. In other words, the more a black hole ”eats,” the brighter the accretion disk will be. On the other hand, a black hole that is not supplied with much material does not have a bright accretion disk, and obviously, as the black hole does not itself emit light, they are difficult to find. The research team calls an isolated black hole that is not provided with a sufficient amount of “food” a “stray black hole.”

*3 Gravitational wave: A phenomenon where a space-time disturbance caused by the motion of a non-axisymmetric body is propagated as a wave at the speed of light. Like the existence of black holes, it was predicted by Einstein’s general theory of relativity and its detection was said to be Einstein’s “final homework.” Its first detection was announced in 2016, exactly 100 years after Einstein completed his general theory of relativity, and it was found that the merging of black holes was the source.

*4 Secondary star: A star system consisting of two stars interacting with each other through gravity and rotating around their common barycenter is called a binary star, with the brighter of the two called the primary star and the fainter called the secondary star. Partners of a binary star are not only limited to stars but in some cases can also be neutron stars or black holes.

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

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