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# A promising view to the Moon: Anticipations for Tianwen-2 samples returned from Kamo'oalewa

**WenZhe Li[1,2], Yong Wei[1,2*], Jian-Yang Li[3], and Wei Yang[1,2]**

[1]Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;

[2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China;

[3]Planetary Environmental and Astrobiological Research Laboratory (PEARL), School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai Guangdong 519082, China

**Key Points:**

- Current knowledge of Kamo'oalewa concerning its physical characteristics, dynamic evolution, surface environment, and origin is reviewed.
- Confirmation of the origin of Kamo'oalewa will be a crucial focus when Tianwen-2 samples are returned to Earth for laboratory analyses.
- Samples from Kamo'oalewa, a possible lunar fragment, will provide additional new insights that will contribute to better understanding the evolutionary history of the Moon and the Earth–Moon system based on the available lunar samples.

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**Abstract:** The exploration of asteroids has received increasing attention since the 1990s because of the unique information these objects contain about the history of the early solar system. Quasi-satellites are a population of asteroids that co-orbit closely with, but are outside the gravitational control of, the planet. So far, only five Earth quasi-satellites have been recognized, among which (469219) Kamo'oalewa (provisionally designated as 2016 $HO_3$) is currently considered the most stable and the closest of these. However, little is known about this particular asteroid or this class of near-Earth asteroids because of the difficulties of observing them. China has announced that Tianwen-2, the asteroid sample-return mission to Kamo'oalewa, will be launched in 2025. Here, we review the current knowledge of Kamo'oalewa in terms of its physical characteristics, dynamic evolution, surface environment, and origin, and we propose possible breakthroughs that the samples could bring concerning the asteroid Kamo'oalewa as an Earth quasi-satellite. Confirming the origin of Kamo'oalewa, from its prevailing provenance as debris of the Moon, could be a promising start to inferring the evolutionary history of the Moon. This history would probably include a more comprehensive view of the lunar farside and the origin of the asymmetry between the two sides of the Moon. Comparing the samples from the Moon and Kamo'oalewa would also provide new insights into the Earth wind.

**Keywords:** Tianwen-2; Kamo'oalewa (2016 $HO_3$); returned samples; evolutionary history of the Moon; the Earth–Moon system

## 1. Introduction

Small bodies, such as asteroids, attract considerable attention and interest in our journey of space exploration, not only for their risk of impact to the Earth, but also for the unique information they provide about the formation and evolution of planets and life in the solar system. Among the near-Earth asteroids (NEAs), Earth quasi-satellites are a special dynamic group that co-orbit the Sun closely with the Earth (Sharkey et al., 2021). They are distinguished from true satellites by their orbits, orbiting the Sun and lying completely outside the Earth's Hill sphere. Currently, only five such objects have been recognized. Another possible Earth quasi-satellite, 2023 $FW_{13}$, requires further study to confirm its status (Newsletter March 2024, European Space Agency Near-Earth Objects Coordination Centre, https://neo.ssa.esa.int/documents/d/guest/newsletter-march-2024). These special asteroids may represent a population of poorly understood objects and are therefore of particular scientific interest.

One of the confirmed quasi-satellites of the Earth (469219), Kamo'oalewa (provisionally designated as 2016 $HO_3$), was discovered by the Pan-STARRS 1 (Panoramic Survey Telescope and Rapid Response System 1) survey telescope at Haleakala Observatory on April 27, 2016 (e.g., Fenucci and Novaković, 2021). Dynamic analyses have indicated that it is the closest and most stable of the five Earth quasi-satellites confirmed so far (e.g., de la Fuente Marcos and de la Fuente Marcos, 2016; Fenucci and Novaković, 2021; Castro-Cisneros et al., 2023). Several recent studies have suggested that it may have originated from the Moon (e.g., Sharkey et al., 2021; Castro-Cisneros et al., 2023; Jiao YF et al.,

First author: W. Z. Li, liwenzhe23@mails.ucas.ac.cn
Correspondence to: Y. Wei, weiy@mail.iggcas.ac.cn
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2024). However, only a small set of observational data are available, which considerably limits our understanding of this asteroid.

Considering the scientific significance and engineering feasibility of Kamo'oalewa, some space missions have chosen it as a target, including Tianwen-2, a sample-return mission of the China National Space Administration that will be launched in 2025 (Wei Y et al., 2018). Three main scientific objectives are proposed for the Tianwen-2 mission: (1) to explore the dynamic evolution of Kamo'oalewa by measuring its physical parameters, such as orbit, rotation, shape, size, and thermal radiation; (2) to investigate its morphology, composition, and possible inner structure; and (3) to determine the basic physical properties; chemical, mineral, and isotope compositions; textures; and structures of the samples, which would probably provide information on the origin, formation, and evolution of the solar system.

In addition to improving our understanding of Kamo'oalewa and other quasi-satellites of the Earth, the asteroid samples returned by Tianwen-2 could provide insights into the evolution of the Moon, considering its possible lunar origin. Such a profound understanding could possibly help clarify some vague issues related to the evolution of the Moon and even the Earth–Moon system.

## 2. Current Knowledge of Kamo'oalewa

### 2.1 Basic Physical Characteristics

Keeping a heliocentric orbit of 1:1 mean motion resonance with the Earth, Kamo'oalewa is currently recognized as an Earth co-orbital asteroid and a quasi-satellite (de la Fuente Marcos and de la Fuente Marcos, 2016; Fenucci and Novaković, 2021; Castro-Cisneros et al., 2023). It belongs to the Apollo-class NEAs, with a semi-major axis of 1.0009 astronomical units (au), an eccentricity of 0.1027, and an inclination of 7.7962° (International Astronomical Union, Minor Planet Center, https://minorplanetcenter.net/db_search/show_object?object_id=469219).

The rotational period of Kamo'oalewa is 28.3 (+1.8/−1.3) minutes. Its diameter ranges from 46 to 58 m, assuming an absolute magnitude of 24.3 and a possible range of albedos from 0.10 to 0.16 (Sharkey et al., 2021). Because of the lack of direct measurements and its small size, its shape is unknown. Some studies have suggested that Kamo'oalewa has an elongated shape, based on the light curve data (Fohring et al., 2018; Li XY and Scheeres, 2021). Further numerical experiments for a more detailed view of its physical properties have assumed triaxial ellipsoidal shape models for Kamo'oalewa. For example, within the proposed models of Li XY and Scheeres (2021), the width-to-length ratio of Kamo'oalewa was suggested to be smaller than 0.48. They showed that the gravitational acceleration on its surface is on the order of $10^{-5}$ m/s$^2$ in their models (assuming a density $\rho$ = 2700 kg/m$^3$).

### 2.2 Dynamic Evolution

The dynamic evolution of Kamo'oalewa has been investigated mainly by extensive N-body simulations and the statistical results of numerical integrations. Kamo'oalewa is believed to have remained in its quasi-satellite state for nearly 100 years and will stay for approximately another 300 years, after which it will switch to a horseshoe orbit (de la Fuente Marcos and de la Fuente Marcos, 2016; Castro-Cisneros et al., 2023; Figure 1). The transition between these two co-orbital states will repeat, but this asteroid will still be located within the Earth's co-orbital zone during this dynamic evolution (de la Fuente Marcos and de la Fuente Marcos, 2016; Castro-Cisneros et al., 2023). Numerical models have shown that these transitions will happen when the orbital nodes of Kamo'oalewa arrive at the farthest place from the Earth, where the gravitational effect of the Earth–Moon system reaches the weakest point (de la Fuente Marcos and de la Fuente Marcos, 2016). In addition, the switching behaviors are possibly regulated by the unstable periodic orbits associated with the axial orbits of the Sun–Earth Lagrange points (Oshima, 2018).

de la Fuente Marcos and de la Fuente Marcos (2016) suggested that over the longer term, Kamo'oalewa might remain within the Earth's co-orbital zone for at least 1 megayear (Myr). However, this time span could be shortened (still at least 0.5 Myr) when the

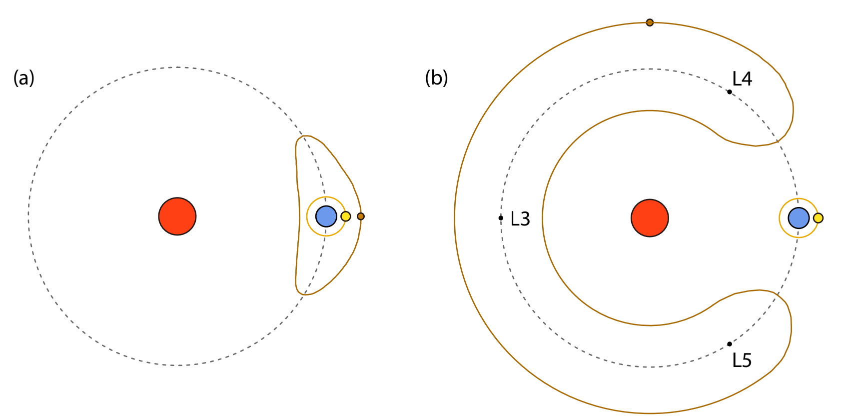


**Figure 1**. Two types of co-orbital states related to Kamo'oalewa (not to scale). (a) The co-orbital state (quasi-satellite) of Kamo'oalewa (brown line) at present. The red, blue, yellow, and brown circles represent the Sun, the Earth, the Moon, and Kamo'oalewa, respectively. The gray dashed line and the yellow line show the orbits of the Earth and the Moon, respectively. The distance of Kamo'oalewa from the Earth is 38 to 100 lunar distances, far from the sphere of gravitational influence of the Earth. (b) Kamo'oalewa will switch into a horseshoe orbit about 300 years later. L3, L4, and L5 are the three Lagrange points of the Sun–Earth system. Modified from Castro-Cisneros et al. (2023).

Yarkovsky effect is considered (Fenucci and Novaković, 2021). Some studies have pointed out that both gravitational and non-gravitational effects (especially the Yarkovsky effect) could be important for small bodies such as Kamo'oalewa, particularly in the time frame of >$10^6$ years (Fenucci and Novaković, 2021). The comparative contributions of these factors to the dynamic evolution of Kamo'oalewa remain to be understood once more highly accurate physical parameters of the asteroid become available. Nevertheless, the effects of some of these factors have been discussed so far. For example, the idea of the notable influence of Jupiter on the secular orbital evolution of Kamo'oalewa has been proposed, such that changing the mass of Jupiter or even removing it would have great effects on the numerical calculations (de la Fuente Marcos and de la Fuente Marcos, 2016). Researchers have also found that the Kozai–Lidov effect has no influence on Kamo'oalewa at present (de la Fuente Marcos and de la Fuente Marcos, 2016; Dermawan, 2019). The Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect, which may affect the rotational state of Kamo'oalewa (de la Fuente Marcos and de la Fuente Marcos, 2021; Fenucci and Novaković, 2021), is still highly uncertain because this effect is sensitive to the shape and thermal properties of a body, which are completely unknown for Kamo'oalewa (Fenucci and Novaković, 2021). In addition, all studies have suggested that the probability of Kamo'oalewa impacting the Earth is negligible (de la Fuente Marcos and de la Fuente Marcos, 2016; Fenucci and Novaković, 2021; Gur'yanov and Galushina, 2021).

Although the accuracy of the key parameters is limited (e.g., shape, density, thermal conductivity), Kamo'oalewa is still considered the most stable among the known Earth's co-orbitals in terms of its dynamic evolution (de la Fuente Marcos and de la Fuente Marcos, 2016; Fenucci and Novaković, 2021).

### 2.3 Surface Environment

On the basis of spectral observations, Kamo'oalewa is classified as an L-type or S-type asteroid, with the former being more likely (Reddy et al., 2017; Fohring et al., 2018; Fenucci and Novaković, 2021), both suggesting that it has a silicate composition (Fenucci and Novaković, 2021; Sharkey et al., 2021). However, its spectrum is inconsistent with those of typical S- or L-type NEAs, and the most notable difference is the much redder spectral slope of Kamo'oalewa (Sharkey et al., 2021). This spectral slope could be caused by several factors, such as metal content, particle size, and space weathering. Comparisons with the spectra of lunar samples suggest that lunar-style space weathering is the most likely factor (Sharkey et al., 2021).

The dynamic properties and distribution of the regolith on the surface of Kamo'oalewa likely differ from those of other asteroids investigated by exploratory missions to date because of Kamo'oalewa's possible elongated shape, fast spin, small size, and weak gravity (Li XY et al., 2023). Numerical simulations using different assumed shapes have indicated that all particles would escape from Kamo'oalewa in hours or days if a disturbance occurred in the failed regolith (Li XY and Scheeres, 2021). Depending on their original states, these disturbed particles would escape directly or undergo processes such as impacting, rebounding, jumping, or sliding before escaping (Li XY and Scheeres, 2021). Despite the unstable and complex dynamic environment on the surface of Kamo'oalewa, grains smaller than 1 mm to 1 cm are expected to exist there, with the polar regions and the ends of the short axis the most likely places to find them (Li XY and Scheeres, 2021). By comparison, millimeter- and larger-sized particles have been observed on the surfaces of the asteroids Eros and Itokawa, and centimeter-sized particles exist on the surface of the asteroid Bennu (Miyamoto et al., 2007; Walsh et al., 2019; Li XY and Scheeres, 2021).

Given the dynamic environment and possible existence of particles, the polar regions of Kamo'oalewa have been considered the best places for landing and sampling (Li XY and Scheeres, 2021; Li XY et al., 2023). In addition, sampling without contact, for example, blowing the surface with the spacecraft thrust (e.g., DellaGiustina et al., 2023) and then collecting the ejected particles, may be a feasible method that takes advantage of the unstable dynamic state of the failed regolith on its surface (Li XY and Scheeres, 2021).

### 2.4 Origin

The origin of Kamo'oalewa is still unknown. Three possibilities have been proposed so far: capture, fragment of the parent body, and debris from previous space flight missions. Among them, the third possibility has mostly been ruled out, given the similarities of its rotation and the spectrum to other small near-Earth objects (NEOs; Fenucci and Novaković, 2021). The capture origin hypothesis says that Kamo'oalewa may have come from the main asteroid belt (Morais and Morbidelli, 2002; de la Fuente Marcos and de la Fuente Marcos, 2016; Fenucci and Novaković, 2021), the near-Earth population (Sharkey et al., 2021), or the family of Earth's Trojan asteroids (Malhotra, 2019; Sharkey et al., 2021). If it is a fragment, its parent body could be the Moon (Gladman et al., 1995; Sharkey et al., 2021; Castro-Cisneros et al., 2023), an NEO (Holsapple and Michel, 2008; Sharkey et al., 2021), or asteroid (234) Barbara or a Barbarian family member (Fenucci and Novaković, 2021). Considering the characteristics of the reflectance spectrum (Sharkey et al., 2021), the lunar surface has become a prevailing hypothesis for its source (by impact). Recently, evaluation of this hypothesis through numerical simulations has suggested that only a small portion of the impact ejecta (less than 6.6% of cases) would reach a co-orbital state similar to that of Kamo'oalewa (Castro-Cisneros et al., 2023). They found that the likely source was the trailing side of the Moon, with a launch velocity slightly higher than the escape velocity. Combining the results of numerical simulations with current understanding of the lifetime of NEAs, Jiao YF et al. (2024) hypothesized that Kamo'oalewa could have come from the Giordano Bruno crater, a young crater (1–10 Ma) 22 km in diameter located on the farside of the Moon.

## 3. Expectations for the Returned Samples

Detailed reconnaissance during the orbit phase is crucial for providing context, including the overall characteristics, the formation and evolutionary history, and the sampling site selection. On the basis of its possible lunar origin, lunar-style space weathering would be expected for the surface of Kamo'oalewa, represented by a red spectral slope for the reflectance spectrum similar to that of the Moon. Compositions similar to those of the lunar surface would also be expected in remote sensing data.

The structure of Kamo'oalewa as a rubble pile or a monolithic body remains uncertain. Cheng B and Baoyin HX (2024) predicted that the surface strength and the bulk cohesion for Kamo'oalewa needed to be larger than approximately a few pascals and ~10 to 30 Pa, respectively. Therefore, they suggested that the monolithic structure would be more likely, considering the strength conditions of rubble-pile asteroids surveyed *in situ* previously (Cheng B and Baoyin HX, 2024). Nevertheless, the rubble-pile structure has not been completely excluded because the difference between the required strength for Kamo'oalewa (tens of pascals) and the typical strength for a rubble-pile structure (within the pascal range) is not decisively large (Cheng B and Baoyin HX, 2024). Accurate estimations of the density by measurements of mass and shape, the porosity by thermal imaging (Okada et al., 2020), and the internal structure by radar instruments would all contribute to determining the mechanical properties of Kamo'oalewa.

If Kamo'oalewa were found to be a rubble pile, mass movement would be expected on its surface, possibly manifested by the uneven distribution of boulders and the erasure of small craters, as suggested for Bennu, Ryugu, Itokawa, and Eros (Veverka et al., 2001; Michel et al., 2009; Sugita et al., 2019; Jawin et al., 2020). These material migrations would lead to different exposure ages on the surface (Sugita et al., 2019), which is an important factor to consider when choosing the sampling site. Considering the short spin period of Kamo'oalewa, the direction of migration of its surface materials may be more similar to that of Bennu than that of Ryugu, with the downslope direction toward the equator. Therefore, regions in the mid-latitudes may have shorter exposure ages than those in the equatorial region. In addition, the polar regions should be stable (Sánchez and Scheeres, 2020). Therefore, we can expect relatively pristine samples of Kamo'oalewa from the mid-latitude regions to confirm its lunar origin and conduct other lunar-related analyses. Accurate determination of the direction of migration of surface materials on Kamo'oalewa relies on detailed investigations of its geopotential, the shape model, and high-resolution observations of the regolith deposits and boulder distributions (Sugita et al., 2019; Jawin et al., 2020).

Considering our limited understanding of Kamo'oalewa, samples returned from Kamo'oalewa could achieve possible breakthroughs in the following areas:

(a) Accurate measurements of the thermal conductivity of the Kamo'oalewa samples will help constrain the model of the thermal properties of its regolith. Together with the remote sensing measurements, such as thermal infrared imaging conducted during the orbit phase, these results will help estimate the porosity of Kamo'oalewa (e.g., Okada et al., 2020). All combined, we can further constrain our thermophysical model for Kamo'oalewa, thus accurately evaluating the influence of the YORP and Yarkovsky effects. In addition, these results could be generalized to revise our estimations of the thermal properties of other asteroids with similar surface compositions, which would improve our understanding of the dynamic evolution of small NEAs.

(b) Analyzing the size and size distribution of sample particles will contribute to our knowledge of the regolith properties and thus provide some clues to the evolution of the regolith on Kamo'oalewa. Asteroid regolith generally originates from micrometeorite impacts and thermal fragmentation and is lost as a result of multiple removal mechanisms, including rotational fission, particle ejection, solar radiation pressure, and electrostatic effects (Scheeres, 2007; Lauretta et al., 2019; Hsu et al., 2022). However, relevant studies are still inadequate for asteroids of tens of meters in scale, particularly those spinning fast like Kamo'oalewa (Li XY and Scheeres, 2021). A better understanding of the production and removal processes of fine-grained particles among asteroids of a wide range of sizes is of great importance, considering that the retention of fine grains is a key factor affecting thermal inertia. This physical parameter would affect the Yarkovsky effect, a key factor in supplying NEAs from the main asteroid belt (Bottke et al., 2006; Hsu et al., 2022). Therefore, we anticipate that samples returned from this small and unique asteroid, together with the spectral and thermal observations in the orbit phase of Tianwen-2, will help fill the gap in regolith formation, preservation, and evolution processes on different types of asteroids and in various dynamic environments (Sánchez and Scheeres, 2020). In addition, comparisons with samples from other asteroids, such as Ryugu, Bennu, and Itokawa, will play an important role in understanding the evolutionary processes of regolith in the asteroid population.

(c) Connections between the spectral data from remote sensing observations, meteoritic analogues, and Kamo'oalewa will be established by a full analysis of the chemical, mineral and isotopic compositions, textures, and structures of samples from Kamo'oalewa. These could help us better understand multiple means of observations and Kamo'oalewa itself.

(d) We also expect U-rich minerals, such as zircons, to be included in the returned samples for age dating, which will further constrain the formation and evolutionary history of Kamo'oalewa. Exposure ages measured by cosmogenic nuclides (such as the cosmogenic noble gases $^{3}$He, $^{21,22}$Ne, $^{38}$Ar, $^{78,80}$Kr, and $^{124,126}$Xe) and cosmogenic radionuclides (Wieler and Graf, 2001) in samples, especially from stable regions such as the polar regions (Sánchez and Scheeres, 2020), will provide information on the time of the impact event ejecting Kamo'oalewa from the Moon.

(e) The returned samples may provide information on the process of the impact event that ejected Kamo'oalewa. Possible minerals with shock metamorphic features related to the impact event will furnish knowledge of this impact event and the impact processes happening off the Earth. These impact features may include information such as the temperature, pressure, and duration of this impact event, providing more accurate constraints on the shock conditions for impact dynamics simulations. The dynamic routines of ejecta could be revealed by using the improved impact model, which would also provide important clues about other undiscovered lunar meteorites.

(f) The most exciting expectation may be the information carried in the returned samples regarding the origin of Kamo'oalewa. Direct comparison of the mineral and isotopic compositions of samples between the Moon and Kamo'oalewa will help determine whether it is a fragment of the Moon, thus helping support or refute the currently popular lunar origin hypothesis. If the Moon is indeed the parent body of Kamo'oalewa, then it would be the first fragment of the Moon recognized as an NEA so far (Castro-Cisneros et al., 2023). Furthermore, comparisons among samples from Luna 24 (likely containing ejecta of the Giordano Bruno crater; Basilevsky and Head, 2012), Yamato-82192/82193/86032 (meteorites likely from the Giordano Bruno crater; Fritz, 2012), and Kamo'oalewa will help us test the recent hypothesis of the lunar crater Giordano Bruno as the origin of Kamo'oalewa (Jiao YF et al., 2024).

If Kamo'oalewa is suggested to come from other bodies, such as Barbarian asteroids instead of the Moon, then this could be another equally exciting development because Barbarians are considered to contain the oldest solid materials in the solar system (Fenucci and Novaković, 2021). If Kamo'oalewa is a fragment of this family, accounts of how materials and planets formed at the beginning of the solar system would be expected.

Understanding the origin of Kamo'oalewa may also help us recognize other possible fragments of the same parent body, based on its characteristics. Whether the origin of this body is the Moon, a Barbarian asteroid, or another source, it will provide a new, more comprehensive perspective on our solar system.

Therefore, the combined results of measurements during the orbit phase (e.g., mass, shape, structure), laboratory analyses of returned samples, and spectral analyses of the remote sensing data will further help constrain the formation and evolutionary processes of Kamo'oalewa. These investigations could potentially become a start toward understanding the quasi-satellite population of the Earth, a special group about which we currently have little knowledge. Additionally, being an asteroid ranging in size from 46 to 58 m, Kamo'oalewa is much smaller than any other asteroid visited by previous missions (Cheng B and Baoyin HX, 2024). As an NEO, it falls in the size range of having a high expected impact frequency, ~$1.07 \times 10^{-3}$ to ~$6.19 \times 10^{-4}$ per year (Stokes et al., 2003). The Tianwen-2 mission will thus also contribute to filling this important gap within the NEA populations.

## 4. A Promising View from Its Origin to the Moon

Being possibly the first fragment of the Moon recognized as an NEA, Kamo'oalewa may retain some records of the evolutionary history of the Moon and the Earth–Moon system. If it originated from the Moon, given that many lunar samples are available, an important question would be, "What additional or unique information about the Moon and the Earth–Moon system could the Kamo'oalewa sample bring us compared with the returned lunar samples?" We believe that Kamo'oalewa will present a promising new view of the Moon and the Earth–Moon system in at least two areas.

The first question is from which impact crater on the Moon Kamo'oalewa originated. Confirming the source crater for Kamo'oalewa could improve our understanding of the shock conditions of this impact (e.g., impact velocity and angle) and the possible size of the impactor based on the accurate size of the crater. The source impact crater could be identified by combining the mineralogical, geochemical, and spectral characteristics of the sample returned from Kamo'oalewa, with numerical simulations used to study the impact event according to the size and orbit of this asteroid. If Kamo'oalewa did come from the Giordano Bruno crater, as suggested by dynamic modeling (Jiao YF et al., 2024), we may gain a better understanding of the lunar farside by combining the information from the Chang'e-6 and Tianwen-2 missions. The China National Space Administration has obtained lunar farside samples for the first time, returned by the Chang'e-6 mission from the precise landing site located at 41.6383°S, 153.9856°W (Liu ZQ et al., 2024). Samples from these two missions (Tianwen-2 and Chang'e-6, including both the northern and southern hemispheres of the lunar farside; Figure 2) will provide us with a more general picture of the lunar farside based on the petrological, mineralogical, and geochemical characteristics. In addition, combining the analyses of lunar nearside samples from the previous missions may help constrain the evolutionary history of the Moon and provide clues that reveal the origin of the asymmetry between the two sides. On the other hand, if the Giordano Bruno crater is rejected as the origin of Kamo'oalewa, reexploring the source crater will provide an opportunity to revise and improve our impact models and the understanding of subsequent dynamic processes.

Second, Kamo'oalewa could help verify our understanding of the Earth wind and thus ideally provide us with an alternative view of planet–moon systems. The Earth wind is a collection of particles from the Earth's magnetosphere (e.g., $H^+$, $He^+$, $O^+$, $NO^+$, $O_2^+$), consisting of both the solar wind particles entering the magnetosphere and terrestrial ions escaping from the Earth's ionosphere

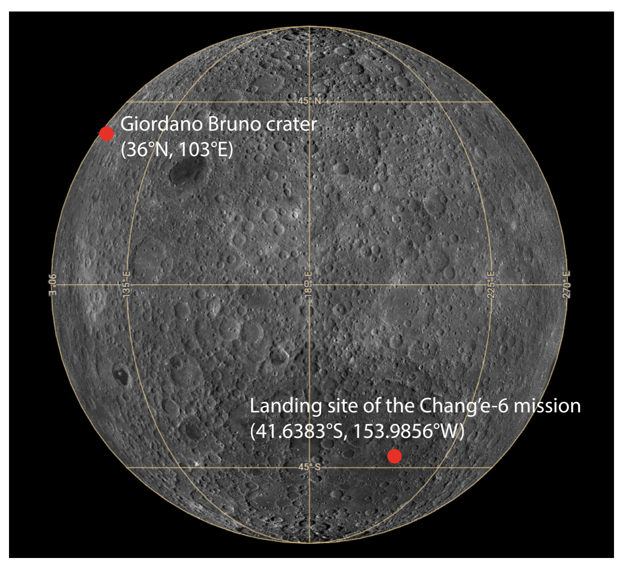


**Figure 2**. Location of the Giordano Bruno crater and the landing site of the Chang'e-6 mission. The two red circles show the locations of the Giordano Bruno crater (the possible origin of Kamo'oalewa) and the landing site of the Chang'e-6 mission (Liu ZQ et al., 2024) on the farside of the Moon. The map of the lunar farside is from LROC (Lunar Reconnaissance Orbiter Camera) QuickMap (https://quickmap.lroc.asu.edu/projections?prjExtent=-1594681.2981205%2C-909717.6478905%2C1594681.2981205%2C766092.1105477&showGraticule=true&layers=NrBsFYBoAZIRnpEBmZcAsjYIHYFcAbAyAbwF8BdC0yioA&proj=7).

and the upper atmosphere (Wang HZ et al., 2021; Cao JB et al., 2024). The Moon passes through the Earth's magnetosphere for one-quarter of the time of each orbit around the Earth (Cao JB et al., 2024), during which time it is possibly being affected by the Earth wind. Ozima et al. (2005) hypothesized that most of the nitrogen and some of the volatile elements on the lunar nearside soils are implanted from the Earth. Wei Y et al. (2020) further suggested that both the nearside and farside lunar soils may contain these particles implanted from the Earth. Additionally, Earth wind particles have been observed in the lunar orbit, and Harada et al. (2014) suggested that the Earth wind can reach the Moon (Zhou XZ et al., 2013; Harada et al., 2014; Poppe et al., 2016). In comparison, Kamo'oalewa, which is far away from the Earth (38 to 100 lunar distances from the Earth; de la Fuente Marcos and de la Fuente Marcos, 2016) and spends most of its time outside the Earth wind, receives a lower quantity of particles from our planet compared with the Moon (Figure 3). Therefore, Kamo'oalewa becomes an appropriate reference to the Moon to verify the constituents of the Earth wind and to help recognize the results of the interaction between the Earth wind and these kinds of airless bodies, especially considering the possible origin of Kamo'oalewa as a lunar fragment. If the model of Earth wind implantation is correct, we will find fewer particles related to the Earth wind in samples from Kamo'oalewa, such as less $^{15}N$ enrichment and fewer volatile elements, compared with both the nearside and farside lunar samples returned from previous lunar sample-return missions and from Chang'e-6. Combined with further studies on the environment of the Earth's magnetosphere, the escaping rate of Earth wind particles/ions (as measured by such instruments as neutral atom imagers and magnetometers; Cao JB et al., 2024), and the transport mechanisms of Earth wind particles, these understandings may provide us with a new approach to studying the history of geomagnetic fields and the ancient atmosphere (Wei Y et al., 2020), and, by extension, the interactions between planets through planet wind (including planets, satellites, and asteroids).

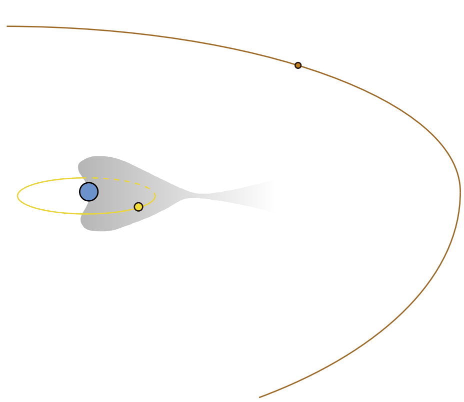

**Figure 3**. The current orbit of the Moon and Kamo'oalewa in the background of the Earth wind (not to scale). The blue, yellow, and brown circles represent the Earth, the Moon, and Kamo'oalewa, respectively. The yellow and brown lines show the orbits of the Moon and Kamo'oalewa. The main region of particles escaping from the Earth is shown in gray (Wei Y et al., 2020). Kamo'oalewa is 38 to 100 lunar distances away from the Earth, resulting in less influence than the Moon from particles escaping from the Earth.

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