(469219) Kamoʻoalewa, A Space-Weathering-Matured Old-Age LL-chondrite-like Small NEA: Target of the Tianwen-2 Sample Return Mission

Pengfei Zhang[1], Yang Li[1]*, Guozheng Zhang[2], Xiaoran Yan[3], Yongxiong Zhang[4], Pierre Vernazza[5], Edward Cloutis[6], Takahiro Hiroi[7], Mikael Granvik[8], Xiaoping Zhang[2], and Yangting Lin[9], [1]Institute of Geochemistry, CAS, Guiyang, China (zhangpengfei4524@gmail.com; *liyang@mail.gyig.ac.cn), [2]Macau University of Science and Technology, Macau, China, [3]Tsinghua University, Beijing, China, [4]Guangzhou College of Technology and Business, Guangzhou, China, [5]Aix Marseille Université, CNRS, CNES, Laboratoire d'Astrophysique de Marseille, Marseille, France, [6]University of Winnipeg, Winnipeg, Canada, [7]Brown University, Providence, USA, [8]University of Helsinki, Helsinki, Finland, [9]Institute of Geology and Geophysics, CAS, Beijing, China.

Introduction: So far, three asteroid sample-return missions, Hayabusa, Hayabusa 2, and OSIRIS-REx to asteroids have greatly increased our knowledge of hundreds-meter rubble-pile NEAs. However, also limited by ground-based observation resolution, little is known about smaller near-Earth asteroids (NEAs). Now, the China National Space Administration has proposed a new asteroid mission, Tianwen-2, which plans to first return a sample of an S-type sub-hundred-meter Earth quasi-satellite (469219) 2016 HO_3 Kamoʻoalewa, and then conduct in-orbit investigations of a main belt active asteroid: 311P/PANSTARRS. Here, we report that Kamoʻoalewa is a space-weathering (SW)-matured LL-chondrite-like object originating from the inner main belt Flora family.

Results: We first determined the composition of Kamoʻoalewa by comparing Kamoʻoalewa's reflectance spectrum (which was previously obtained by the Large Binocular Telescope and the Lowell Discovery Telescope from 2017 to 2021 [1]) with that of meteorites. As a result, Kamoʻoalewa shows an absorption center at 0.984 µm, only falling into the range of LL-chondrites. (Fig. 1), suggesting that Kamoʻoalewa resembles LL chondrites in composition rather than other meteorite types.

Then we performed an orbital dynamical calculation by employing the "Granvik seven-region escape model" [2] to trace the source region of Kamoʻoalewa. As a result, Kamoʻoalewa shows a probability of 72 ± 5% originating from the ν6 secular resonance. Given that Flora family adjacent to the ν6 secular resonance has been known as the major source region of LL-chondrite-like NEAs, such a high probability, therefore, emphasizes the possibility that Kamoʻoalewa is an LL-chondrite-like asteroid.

Particularly, we note that Kamoʻoalewa shows an extremely red (step) spectral slope (0.726, calculated within 0.45-2.194 µm region by liner fitting) when compare with NEAs and main belt asteroids (MBAs) (Fig. 2), implying that Kamoʻoalewa is a strongly space-weathered asteroid. Our nanosecond laser irradiation experiment on LL5/6 chondrite Kheneg Ljouâd's powder (simulate long-term SW processes driven by micrometeoroid bombardments) has successfully produced a slightly redder spectrum than Kamoʻoalewa (Fig. 3), strongly proving that Kamoʻoalewa's extremely red-sloped spectrum can indeed be contributed by SW processes. Furthermore, employing the radiative transfer mixing model [3-4], our calculation suggests that 0.29 ± 0.05 wt.% $SMFe^0$ (sub-microphase metallic iron, a major SW product that darkens and reddens silicate asteroids) in Kamoʻoalewa's regolith is required. This is higher than the average content of $SMFe^0$ in the regolith of Itokawa (~ 0.2 wt.% [5]), suggesting that Kamoʻoalewa is indeed a SW-matured object. This is also consistent with our taxonomy of Kamoʻoalewa as S-type rather than Sq- or Q-type.

We also noted that Kamoʻoalewa's spectrum is redder than the mean spectrum of its source region Flora family (which has an exposure age of 0.5-1 × 10^9 year). Given that the SW rate at 1 AU area is about 10 times that of the main belt area, Kamoʻoalewa's SW timescale is hence estimated as at least 0.5-1 × 10^8 year. This exceeds the timescale of rapid reddening by solar wind irradiation (10^6 yr [6]) and the average dynamical lifetimes of NEAs (10^6 year [7]), indicating that Kamoʻoalewa broke as a fragment in the inner main belt very early and still retains most of the previous (non-near-Earth-space) SW information without significant later surface refreshing.

We also estimated Kamoʻoalewa's rotation period as ~27 min (meaning that it is a single rock), size as 69.45 m × 58.49 m × 51.78 m, and its regolith size on 75.38 % of surface area was lower than 2 cm, suggesting that fine-sized grains dominate Kamoʻoalewa's surface. Meanwhile, when we assumed Kamoʻoalewa has been accelerated to current rotation period with a uniform angular acceleration within the Flora family, the estimation suggests that YORP spin-up lifetime is 4.23 × 10^4 to 4.23 × 10^5 yr. It means that the loss of large-sized grains (fresher) may have started very early and significant accumulation of small-sized grains/dust (maturer) has continued over a very long time (10^7 to 10^8 yr).

Discussion: We explain that Kamoʻoalewa's extremely red spectrum can be comprehensively contributed by long-term SW and weak resurface process: (1) long-term loss of young large-sized grains and the accumulation of mature small-sized materials, (2) small size of Kamo‘oalewa decreases the likelihood of surface refreshing caused by impact, (3) non-rubble pile structure may effectively avoid surface rejuvenation that would be driven by the inside-out movement of materials driven by spin-up and matter mixing driven by meteoroid impact, (4) Kamo‘oalewa did not underwent resurfacing by Earth encounters, because its minimum Earth orbit intersection distance (0.0345 AU) and perihelion (0.898 AU) is much larger than the range of Earth encounters (5-16 times Earth radius [8]), and quasi-satellites generally do not experience flybys with Earth as close as those observed for other co-orbital types.

We further predict that sub-hundred-meter, rapidly spinning silicate-rich NEAs with small perihelion may generally exhibit redder spectral slopes and SW matured surfaces. This is different from the current observation that the “Q-type/S-type” ratio increases with decreasing perihelion distance [9-10].

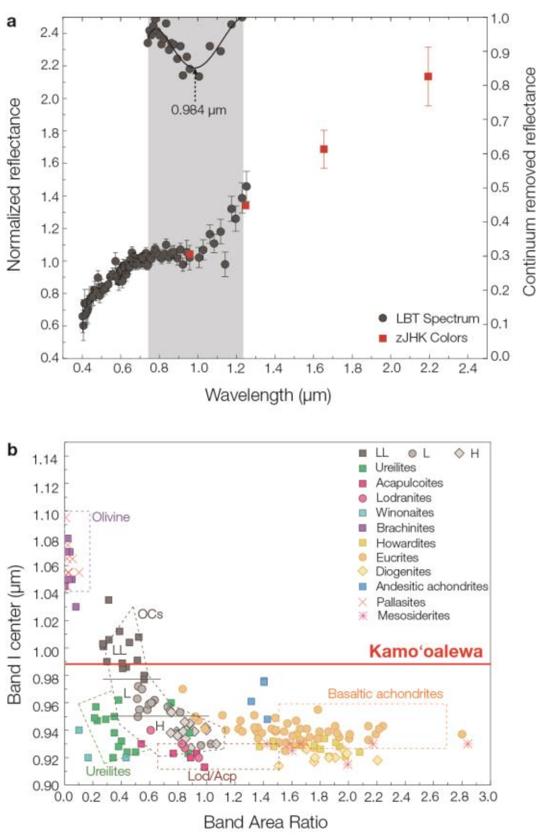

Fig. 1 Spectral matches of Kamo‘oalewa to LL chondrites. (a) Kamo‘oalewa shows a weak 1 μm absorption band (gray shaded region) and the absorption center is 0.984 μm. (b) Comparison of band I center and band area ratio (Band II/Band I) of Kamo‘oalewa with meteorites, the band I center of Kamo‘oalewa (0.984 μm) best matches to LL chondrites.

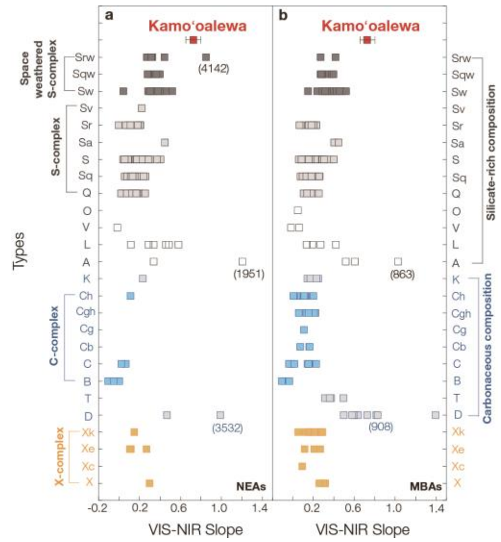

Fig. 2 Comparison of spectral slope of Kamo‘oalewa with NEAs (a) and MBAs (b). Kamo‘oalewa shows a high spectral slope than most of NEAs and MBAs. The asteroid spectral data and types are cited from MITHNEOS [9] and SMASS II [11] respectively.

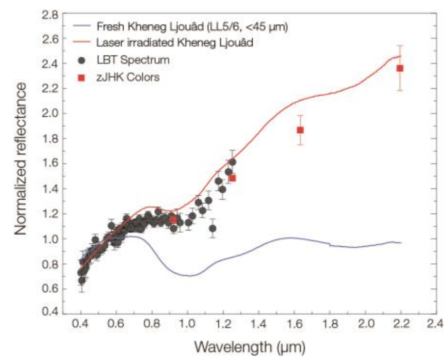

Fig. 3 Comparison of spectra of Kamo‘oalewa with fresh (blue line) and laser irradiated (red line) LL5/6 chondrite Kheneg Ljouâd. After irradiation, Kheneg Ljouâd’s spectrum significantly steeps and slightly steeper than Kamo‘oalewa, suggesting that Kamo‘oalewa-like extremely red spectra can indeed be contributed by long-term SW process.

Reference: [1] Sharkey et al. (2021) *Commun Earth Environ, 2, 1-7*. [2] Granvik and Brown (2018) *Icarus, 311, 271-287*. [3] Lawrence et al. (2007) *JGR: Planets, 112*. [4] Lucey et al. (2011) *Icarus, 212, 451-46*2. [5] Binzel et al. (2001) *Meteorit Planet Sci, 36, 1167-1172*. [6] Vernazza et al. (2009) *Nature, 458, 993-995*. [7] Nesvorný et al. (2017) *AJ, 155, 42*. [8] Nesvorný et al. (2010) *Icarus, 209, 510-519*. [9] Binzel et al. (2019) *Icarus, 324, 41-76*. [10] Demeo et al. (2023) *Icarus, 389, 115264*. [11] Demeo et al. (2009) *Icarus, 202, 160-180*.