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(469219) Kamo'oalewa, A Space-Weathering-Matured LL-chondrite-like Small NEA: Target of the Tianwen-2 Sample Return Mission

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Introduction: Now, the China National Space Administration has proposed an asteroid mission, Tianwen-2, which plans to return a sample of a sub-hundred-meter Earth quasi-satellite (469219) 2016 HO_3 Kamo□oalewa. Early studies suggested Kamo□oalewa originated from the Moon. However, here, we will report that Kamo□oalewa is a space-weathering (SW)-matured LL-chondrite-like object.

Results: We first determined the composition of Kamo□oalewa by comparing Kamo□oalewa’s reflectance spectrum (which was previously reported by [1]) with that of meteorites. As a result, Kamo□oalewa shows an absorption center at 0.984 μm, only falling into the range of LL-chondrites. (Fig. 1), suggesting that Kamo□oalewa resembles LL chondrites in composition rather than other meteorite types.

Then we used an orbital dynamical calculation method [2] to trace the source region of Kamo□oalewa. As a result, Kamo□oalewa 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 Kamo□oalewa is an LL-chondrite-like asteroid.

Particularly, Kamo□oalewa shows an extremely red spectral slope (0.726, calculated within 0.45-2.194 μm) when compare with NEAs and main belt asteroids (MBAs), implying that Kamo□oalewa is a strongly space-weathered asteroid. Our nanosecond laser irradiation experiment on LL5/6 chondrite Kheneg Ljouâd’s powder has successfully produced a slightly redder spectrum than Kamo□oalewa (Fig. 2), proving that Kamo□oalewa’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 Kamo□oalewa'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 Kamo□oalewa is indeed a SW-matured object. This is also consistent with our taxonomy of Kamo□oalewa as S-type rather than Sq- or Q-type.

We also noted that Kamo□oalewa'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, Kamo□oalewa'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 Kamo□oalewa 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 Kamo□oalewa'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 Kamo□oalewa's surface. Meanwhile, when we assumed Kamo□oalewa 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 Kamo□oalewa'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 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 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

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