Assessing the Origins of Earth Quasi-Satellite (469219) Kamo`oalewa. B.N.L. Sharkey[1], V. Reddy[1], R. Malhotra[1], A. Thirouin[2], O. Kuhn[3], A. Conrad[3], B. Rothberg[3,4], J.A. Sanchez[5], D. Thompson[3], C. Veillet[3]

[1]Lunar and Planetary Laboratory, University of Arizona, (1629 E University Blvd, Tucson, AZ 85721, USA), [2]Lowell Observatory (1400 W Mars Hill Road, Flagstaff, AZ 86001, USA), [3]Large Binocular Telescope Observatory (University of Arizona, 933 N. Cherry Ave, Room 552, Tucson, AZ 85721, USA), [4]George Mason University, Department of Physics and Astronomy (MS3F3, 4400 University Drive, Fairfax, VA 22030, USA), [5]Planetary Science Institute (1700 E Fort Lowell Suite 106, Tucson, AZ 85719, USA)

Introduction: Asteroid (469219) Kamo`oalewa is a co-orbital quasi-satellite of the Earth that was discovered in 2016 by the Pan-STARRS survey[1]. Here we report results of a multi-year characterization campaign using the Large Binocular Telescope (LBT) and the Lowell Discovery Telescope (LDT) to determine Kamo`oalewa's rotational and reflectance properties in the visible and near-infrared. Additionally, we review what is known about Kamo`oalewa's orbital history and provide further discussion on hypotheses of its formation.

Spectral Characterization: We report that Kamo`oalewa's reflectance spectrum from 0.4-2.2 microns is atypical when compared to near-Earth asteroids, but closely matches the properties of some lunar highland regolith samples [2] (see Figure 1).

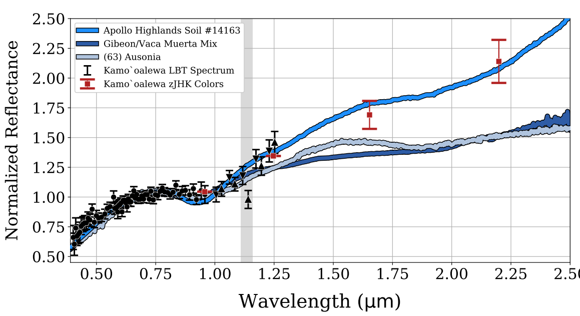

Figure 1. Observed reflectance spectrum of Kamo`oalewa compared with lunar soil, a metal-silicate mixture, and main-belt asteroid (63) Ausonia. The observed slope of the spectrum best matches the reddened spectrum from the lunar highlands sample. From [2].

As displayed in Figure 1, the observed reddened spectral slope (increasing reflectance with increasing wavelength) of Kamo`oalewa matches that of soil samples from the lunar highlands. Although there is a variety of spectral slopes present amongst lunar materials, we demonstrate that Kamo`oalewa's slope of $89^{+12}_{-13}\ \frac{\%}{\mu m}$ is uniquely red when compared to other asteroids (Figure 2). Additionally, we show that a mixture of meteoritic metal with silicates is insufficient to simultaneously explain Kamo`oalewa's slope and the observed 1.0-micron band depth (which is diagnostic of silicate material) (Figure 1, see the curve for the Gibeon/Vaca Muerta Mix).

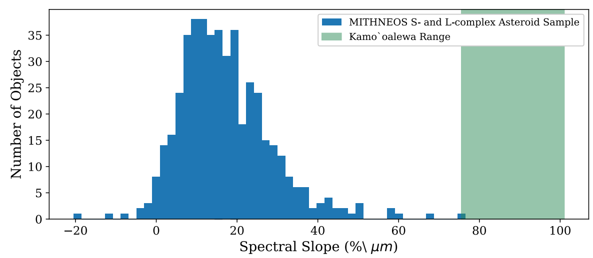

Figure 2. Comparison of the spectral slope derived for Kamo`oalewa compared with the slopes measured from the MITHNEOS survey of near-Earth asteroids [3]. NEA slope histogram. From [2].

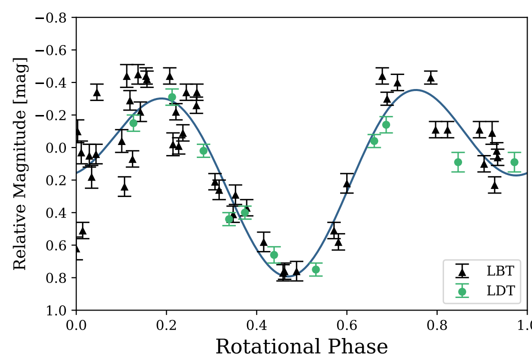

Figure 3. Combined lightcurve of Kamo`oalewa from separate observations from LBT and LDT, phased to the best-fit rotation period of 28.3 minutes. Adapted from [2].

Rotational State: Kamo`oalewa's rotation period has been found to be $28.3^{+1.8}_{-1.3}$ minutes [1,2] and its lightcurve amplitude to be 1.07±0.05mag [2] (see Figure 3). While Kamo`oalewa's rotation period is not extreme in comparison to small near-Earth asteroids, its large lightcurve amplitude (greater than 1.0 magnitudes) combined with a rotation period of $28.3^{+1.8}_{-1.3}$ minutes leads to rapid changes in on-sky brightness that must be accounted for when making color measurements. The capabilities of paired but independent instruments on LBT enabled simultaneous observations of Kamo`oalewa in multiple infrared filters to ensure robust reflectance measurements.

**Kamo`oalewa's Current Orbit:** As shown in Figure 4, Kamo`oalewa's current orbital configuration as a quasi-satellite (in green) will persist for hundreds of years. Although Kamo`oalewa remains outside of the Earth's Hill sphere and is on a heliocentric orbit, during this quasi-satellite configuration its distance from the Earth is always ~0.1-0.3 au. Both before and after this configuration, Kamo`oalewa transitions to a horse-shoe like co-orbital arrangement, where it still has an orbit close to that of the Earth, but its mean longitude drifts relative to the Earth.

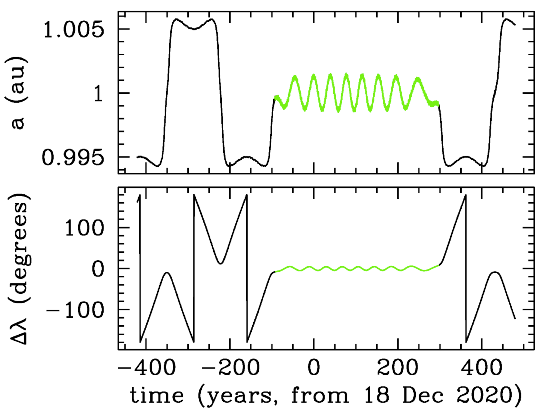

Figure 4. Evolution of Kamo`oalewa's semimajor axis (top) and mean longitude relative to the Earth (bottom). Propagation of Kamo`oalewa's orbit over several hundred years shows that its current quasi-satellite orbit (indicated in green) is preceded and succeeded by a horse-shoe like co-orbital state (indicated in black). Adapted from [2].

**Tracing Kamo`oalewa's Source:** We have identified three distinct sources for Kamo`oalewa. Kamo`oalewa may be a near-Earth object captured recently into its Earth co-orbital arrangement, it may originate from a more stable population of Earth co-orbitals (i.e., Earth Trojans), or it may have an impact origin within the Earth-Moon system. We interpret the combination of Kamo`oalewa's current orbit and its reflectance properties (that match lunar-like silicates more than typical silicate-rich near-Earth asteroids) as supporting a lunar origin.

Next Steps: In addition to further telescopic observations, as well as the possibility of spacecraft study [3-5], detailed characterization of Kamo`oalewa's orbit must be conducted to assess how its orbit has evolved over time and therefore better assess Kamo`oalewa's origins.

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References:

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