ON THE ORIGIN OF THE LARGEST INNER MAIN BELT D-TYPE ASTEROID.

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Introduction: The small body populations of our solar system – including the main asteroid belt, Jupiter's Trojan asteroids and irregular satellites, and Kuiper belt objects – were likely shaped by the early orbital migration of the giant planets. Hence, these bodies are the breadcrumbs by which we can trace back the paths of the giant planets. Here, we discuss additional observations of the innermost (proper orbital semi-major axis ~2.25 AU) D-type asteroid, (336) Lacadiera, whose classification has previously been questioned [1], and discuss its implications for early solar system evolution.

Background: D-type asteroids are thought to have formed beyond the orbit of Neptune, as part of the primordial disk [2,3]. They are characterized by red (steep, positive) slopes in near-infrared wavelengths, weak to absent absorption features, and very low albedos. D-types dominate the Jupiter Trojans and the small body populations beyond Jupiter, along with slightly less red and often brighter P-types, but their presence drops off quickly moving inward from Jupiter [3]. In fact, there are only a handful of D-type asteroids in the inner main belt [4].

Several models of early solar system evolution have tracked the effects of giant planet migration on the primordial reservoirs of small bodies beyond the orbit of Jupiter [5]. These models can broadly account for the present-day distribution of small bodies that carry the signatures of the outer solar system, such as D-type asteroids. However, it has proved challenging to implant bodies inward of about 2.5 AU. The simulations of Vokroulicky et al. 2016 [6], which built upon those of Levison et al. 2009 [1], predict 3 ± 2 objects with D > 30 km and a D or P type classification. This prediction is lower than the observed population by about a factor of 3. They also cannot explain the presence of (336) Lacadiera, which has a diameter of ~63 km [7] and a semimajor axis of 2.25 AU. Due to its large size and roughly spherical shape [8], Lacadiera is unlikely to be a fragment of a collision or to have had its orbit significantly affected by thermal effects. Both previous works that modeled implantation of distant D-types into the Main Belt [1,6] suggest that perhaps Lacadiera has been misclassified. Hence, confirming the taxonomic classification of (336) Lacadiera provides a critical constraint on models of giant planet migration.

Results: The evidence for assessing the taxonomic type of (336) Lacadiera come from recent observations of its albedo and near-infrared reflectance. The Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) collected thermal data on a huge number of moving objects and uses thermal modeling results to estimate sizes and albedos [7]. Of particular interest for (336) Lacadiera is its geometric visible albedo, which was measured to be 5.9%, which is in family with other D-types [4].

Near-infrared spectra was recently obtained as part of a larger survey of D-type asteroid compositions [9]. Gartrelle et al. (2019) observations (0.69-2.5 um) were taken at NASA/IRTF on Mauna Kea using the SpeX instrument in low resolution PRISM mode and the 0.8 - 15" slit on August 6, 2017. Guiding was performed using spillover light from the slit. The asteroid was imaged at 2.2 AU from Earth with an apparent magnitude of 13.47. Ten exposures were obtained at 60 second integration time at an average airmass of 1.05. Reduction was accomplished using SpeXtool to average asteroid reflectance, remove atmospheric interference, and correct for solar color [10]. Normalized at 0.7 microns to a Bus et al. (2002) visible spectra, Figure 1 shows that the near-IR spectra are a very close match to a Bus/DeMeo D-type [11,12].

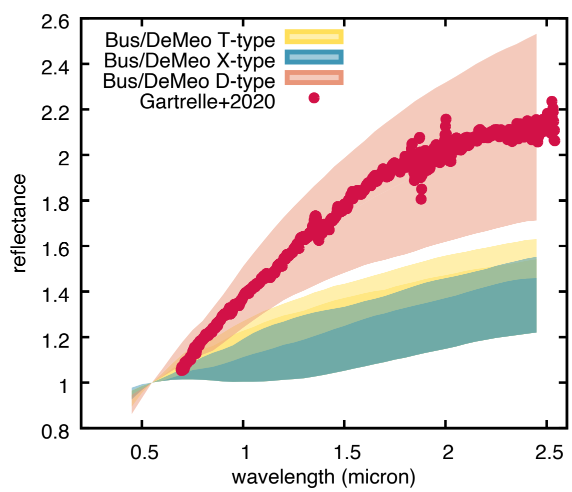

Figure 1: ***Lacadiera's spectrum falls clearly into the range of D-type classifications.*** There is nothing to suggest it is outlier or anything but a D-type asteroid. Observations (0.69-2.5 um, red dots) of (336) Lacadiera were taken at NASA/IRTF on Mauna Kea using the SpeX instrument on August 6, 2017.

Discussion: Compiling recently taken data for (336) Lacadiera shows that it is unequivocally a D-type asteroid. If all D-types were formed beyond Neptune, giant planet migration models need to be able to implant asteroids within 2.3 AU [5]. The most recent models of implantation from the primordial Kuiper Belt into the main asteroid belt by Vokrouhlicky et al. 2016 [6] find that a giant planet instability and reorganization can implant bodies in all regions they are found today. However, the implantation efficiency decreases with decreasing semi-major axis, so the innermost regions, $a <$ 2.5 AU, had an efficiency of only $\sim 0.5 \times 10^{-9}$ per test particle. This value combined with the assumed population of the primordial Kuiper Belt provided an estimate of the largest implanted body in this region being ~50km, with only a total of 3 ± 2 objects with D > 30 km and a D or P type classification. While (336) Lacadiera is a nice match for the expected largest body in the region, when adding it to the tally of other suspected or confirmed bodies, the prediction is lower by more than a factor of two (~10 objects). Furthermore the models did not implant any body with a<2.3 AU, whereas (336) Lacadiera has an a~2.25 AU.

The giant planet instability models are fundamentally chaotic and Vokrouhlicky et al. (2016) [6] utilized two discrete scenarios for their very high resolution simulations that were intended to bracket a range of possible scenarios. In Case 1, a 5th giant planet had a very short interaction with bodies in the inner solar system before being ejected, while in Case 2, the extra giant planet had a longer and deeper adventure in the inner solar system before being ejected. Both are simply cases that end with the correct number and reasonable orbits for the giant planets while not violating constraints for their behavior during the instability. The latter, more violent scenario, generally implanted more objects in the main belt. In light of our findings, there is likely a need for a longer and deeper interaction of an ejected planet to account for an object as large and as close to the Sun as (336) Lacadiera.

Alternatively, it is possible that some D-types formed closer to Jupiter, as part of a primordial population of bodies that was largely scattered and radially-mixed during planet migration [13]. Whether such bodies could be captured into inner main belt orbits with probabilities that match observations has not yet been tested in migration simulations.

Conclusion: Now that we have confirmed (336) Lacadiera's classification as a D-type asteroid, we can consider how it can be used to further our understanding of the early solar system. Later this decade, NASA's *Lucy* mission will explore Jupiter's Trojan asteroids, a population that was almost certainly implanted during giant planet migration and contains bodies with D and P-type spectra. Although limited to flybys, *Lucy* data may shed light on the bulk compositions of these asteroids. A complementary compositional data set of (336) Lacadiera would provide a powerful point of comparison. If (336) Lacadiera and Jupiter's D-type Trojans share the same composition, it would force us to match (336) Lacadiera's current orbit with migration models, a critical constraint. If not, it would reveal the initial composition of a different small body reservoir than we have previously explored and provide constrains on new capture pathways that have not been fully considered.

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