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Supplementary Material for

The solar nebula origin of (486958) Arrokoth, a primordial contact binary in the Kuiper Belt

W. B. McKinnon*, D. C. Richardson, J. C. Marohnic, J. T. Keane, W. M. Grundy,
D. P. Hamilton, D. Nesvorný, O. M. Umurhan, T. R. Lauer, K. N. Singer, S. A. Stern,
H. A. Weaver, J. R. Spencer, M. W. Buie, J. M. Moore, J. J. Kavelaars, C. M. Lisse,
X. Mao, A. H. Parker, S. B. Porter, M. R. Showalter, C. B. Olkin, D. P. Cruikshank,
H. A. Elliott, G. R. Gladstone, J. Wm. Parker, A. J. Verbiscer, L. A. Young,
the New Horizons Science Team†

*Corresponding author. Email: mckinnon@wustl.edu

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This PDF file includes:

New Horizons Science Team (Kuiper Belt Extended Mission Co-Investigators)

S. Alan Stern, Southwest Research Institute, Boulder, CO, USA.

Harold A. Weaver, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Catherine B. Olkin, Southwest Research Institute, Boulder, CO, USA.

John R. Spencer, Southwest Research Institute, Boulder, CO, USA.

J. Wm. Parker, Southwest Research Institute, Boulder, CO, USA.

Anne Verbiscer, University of Virginia, Charlottesville, VA, USA.

Richard P. Binzel, Massachusetts Institute of Technology, Cambridge, MA, USA.

Daniel T. Britt, University of Central Florida, Orlando, FL, USA.

Marc W. Buie, Southwest Research Institute, Boulder, CO, USA.

Bonnie J. Buratti, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

Andrew F. Cheng, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Dale P. Cruikshank, NASA Ames Research Center, Moffett Field, CA, USA.

Heather A. Elliot, Southwest Research Institute, San Antonio, TX, USA.

G. Randall Gladstone, Southwest Research Institute, San Antonio, TX, USA.

William M. Grundy, Lowell Observatory, Flagstaff, AZ, USA.

Matthew E. Hill, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Mihaly Horanyi, University of Colorado, Boulder, CO, USA.

Don E. Jennings, NASA Goddard Space Flight Center, Greenbelt, MD, USA.

J. J. Kavelaars, National Research Council of Canada, Victoria, BC, Canada.

Ivan R. Linscott, Stanford University, Stanford, CA, USA.

Jeffrey M. Moore, NASA Ames Research Center, Moffett Field, CA, USA.

David J. McComas, Department of Astrophysical Sciences, Princeton University, Princeton, NJ, USA.

William B. McKinnon, Washington University in St. Louis, St. Louis, MO, USA.

Ralph L. McNutt, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Alex H. Parker, Southwest Research Institute, Boulder, CO, USA.

Simon B. Porter, Southwest Research Institute, Boulder, CO, USA.

Silvia Protopapa, Southwest Research Institute, Boulder, CO, USA.

Dennis C. Reuter, NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Paul M. Schenk, Lunar and Planetary Institute, Houston, TX, USA.

Mark R. Showalter, SETI Institute, Mountain View, CA, USA.

Kelsi N. Singer, Southwest Research Institute, Boulder, CO, USA.

Leslie A. Young, Southwest Research Institute, Boulder, CO, USA.

Materials and Methods

To model 2-body impacts and potential mergers of granular aggregates, we use PKDGRAV, an N-body code with an implementation of the soft-sphere discrete element method (SSDEM) for collisions between spherical particles. PKDGRAV uses the *k*-d hierarchical tree algorithm to reduce the computational cost of calculating interparticle forces and runs in parallel to reduce the time necessary to perform simulations with large numbers of particles (*41*). SSDEM allows particles to interpenetrate, with restoring forces implemented as springs with a user-adjustable spring constant. The implementation of SSDEM in PKDGRAV has been described in detail (*42*), with implementation of static, rolling, and twisting friction (*101*) and interparticle cohesion (*102*). We only applied cohesive forces between particles of the same progenitor body, i.e., any contact between a particle from one body and a particle from another is treated as cohesionless. This choice was motivated by initial simulations of the binary merger with cohesion included. After an initial contact between bodies, the size of the neck would continue to grow as particles near the contact point stuck together and pulled others along with them. Because we wanted to use cohesion to capture the effect of material strength, we judged this behavior to be unphysical and so adjusted to the model.

We model each lobe of the present contact binary system separately, under the assumption that they formed separately and merged at some point in the past. We generate spherical "rubble piles" out of many smaller particles. We use approximately 135,000 equal-size particles to model LL (diameter 17.94 km) and 63,000 to model SL (diameter 13.64 km); the sizes of lobes were based on preliminary estimates (*7*). Particle radii are normally distributed with a mean radius of 136 m and a standard deviation of 27 m. Upper and lower radius cutoffs are 163 m and 109 m, respectively. After generating LL and SL we run simulations with each body separately to allow the particles to settle into an equilibrium between self-gravitation and repulsive contact forces. Particles are either frictionless or given gravel-like friction parameters—a static friction coefficient of 1.0, a rolling friction coefficient of 1.05, a twisting friction coefficient of 1.3, and a shape parameter of 0.5; the friction parameters mimic the shear strength of irregular particle shapes in contact (*101*). The normal and tangential coefficients of restitution are 0.2. Simulations of direct collisions (Figs. 4A,B) assumed no rotation of the individual bodies before contact, whereas that for Fig. 4C assumed a synchronous rotation rate appropriate to the density; the latter was done to better simulate the possible final merger conditions of a co-orbiting binary.

Supplementary Text

Accretion by hierarchical coagulation

The cold classical Kuiper belt population might have accreted by traditional hierarchical coagulation (*27*). CCKB object formation through a variant of HC has been shown to be viable even in a low-mass (or "light") planetesimal disk (of ~$0.1M_\oplus$), but only if a pre-existing seed population of ~1-km-scale planetesimals is invoked while simultaneously most of the mass is in cm-sized pebbles or smaller (*28*). Formation of km and sub-km scale planetesimals has not been demonstrated for traditional HC models, which was one of the motivations for the development of SI models (e.g., *57*). Models (*28*) typically take 10s to 100s of Myr to accrete the larger bodies of the CCKB, ignore possible dynamical stirring by Neptune, and yield a CCKB that is too massive today (see below).

Characteristic planetesimal mass from the streaming instability

Numerical simulations of SI have focused on the formation of larger (~50-100 km scale) planetesimals in the Kuiper belt, i.e., those at the break in the observed KBO size-frequency distribution (e.g., *24*). We focus on the implications of the SI for a lower-mass, outer protoplanetary disk, i.e., the cold classical region. The gravitational mass scale (M_G) in the streaming instability is given, in the CCKB object region, by $4\pi^5G^2\Sigma_p^3/\Omega_K^4 \sim 10^{14}$ kg × (Σ_p/0.016 kg m^{-2})^3, where Σ_p is the surface mass density in pebbles, Ω_K is the heliocentric orbital frequency, and G is the gravitational constant (*26*). If we adopt $\Sigma_p = 0.016$ kg m^{-2} from (*28*), who spread $0.1M_\oplus$ of solids between 42 and 48 au to form their "light disk," the characteristic planetesimal mass produced by an SI-induced GI would be similar to the mass of Arrokoth (~10^{15} kg), given the sensitivity of M_G to Σ_p. In comparison, to produce a characteristic CCKB object diameter of

~100 km (M_G ~3 × 10^{17} kg) (*103*) requires an order of magnitude more solid mass in pebbles. Neither of these total masses, as planetesimals, violate the surface mass constraint (*20*) for halting Neptune's outward migration.

Because of the limited dynamical excitement of the cold population, (*19*) have argued for modest dynamical depletion of the CCKB, at most, since its formation, perhaps by no more than a factor of ~2. This implies that the mass of sizeable objects in the cold classical region has always been low. Given the very low mass of CCKB objects today (~$0.001M_{\oplus}$ (*103*)), this suggests that the formation of CCKB objects via the streaming (or other) instability —from a larger reservoir of solids that would allow larger bodies than Arrokoth to accrete—must have been intermittent in space and time or otherwise inefficient during the lifetime of the protosolar nebula (*104*). The alternative, that the CCKB was originally more massive and lost substantial mass to collisional grinding (*105*), is not consistent with the lack of evidence for collisional processing of Arrokoth (*7*, *8*) and the large fraction of loosely bound binaries among the cold classicals (e.g., *106*). Sporadic or inefficient planetesimal formation could be related to a globally lower pebble/gas ratio owing to gas drag drift of pebbles (*92*, *94*), but with local pebble concentrations due to zonal flows or other mechanisms (e.g., *107*).

Alternative particle concentration mechanisms to the streaming instability

In addition to SI, nebular turbulence likely led to particle concentrations at corresponding eddy scales (*21*), but whether such concentrations led to GI and planetesimal formation has received less attention (*108, 109*). SI is a dynamic particle concentration mechanism, which is expected to occur over a range of protoplanetary disk conditions and pebble sizes, possibly in tandem with other particle concentration mechanisms (*57*, *110*). For example, the surface mass density of gas in the outermost protosolar nebula, and of the CCKB object formation zone in particular, plausibly should have been low enough for cosmic-ray and x-ray induced ionization and active magneto-rotational instability (MRI) (*57*). Levels of turbulence associated with MRI (*111*) may act to suppress SI, at least in its classic laminar form (*112*). MRI might not reach the disk midplane, however, where SI would take place (*57*, *113*), and SI and MRI can act in tandem, with SI enhancing particle concentrations on a smaller scale (*109*, *114*).

LL and SL as possible Roche ellipsoids

The spin and angular momentum of Arrokoth can be normalized by the critical rotation rate $\omega_c = \sqrt{\frac{4}{3}\pi\rho G}$ and $mR_e^2\omega_c$, respectively, where m and R_e are a body's total mass and equivalent spherical radius (e.g., *99*). The normalized spin and angular momentum for Arrokoth are ~0.29 and ~0.36, respectively, assuming a mass ratio of 2:1 for LL and SL and $\rho = 500$ kg m^{-3} for both lobes. These values resemble those for critically stable Roche ellipsoids of the same mass ratio, about 0.28 and 0.26, respectively (see *99*), but the correspondence breaks down for lower densities (the normalized values scale as $\rho^{-1/2}$).

Shape of Arrokoth's individual lobes

The individual mapped units on LL may indicate the merger or assembly of discrete multi-km-scale planetesimals (*7*, *8*). If so, to create such a lenticular or ellipsoidal body as LL requires that the mergers were themselves not very energetic or high velocity. These velocity conditions would have been met in a collapsing particle cloud (*47*, *58*), but not during heliocentric hierarchical coagulation generally; the latter implies speeds in excess (or greatly in excess) of the escape speed from LL. Low cohesion and a near absence of internal friction would have been necessary mechanically at the time of the LL merger collisions as well. Otherwise, the shape of LL would much more reflect the shapes of the individual subunits from which it was built (as in Fig. 4B).

Alternately, the LL and SL lobes could have accreted directly in a collapsing rotating particle cloud from myriad small pebbles (*47*), and acquired their lenticular shapes naturally. Arrokoth is a contact binary, and not a single, broadly ellipsoidal body, so the dynamical regime that fostered quasi-equilibrium shapes of the individual lobes must not have been applicable when the two bodies themselves finally merged. This suggests that the merger of two lobes (LL and SL) may not have occurred in the pebble cloud itself, but at some later time after the pebble cloud cleared (the latter on an ~10^4 yr time scale (*58*)), when the lobes may have acquired some modest measure of strength (*87*).

Arrokoth's neck appears somewhat bent or tilted in the direction of rotation [(*8*), clockwise in their figure 1A], as if this was due to a final, tangential mass displacement at the contact surface during a merger. Alternately, the bending could be due to some later mechanical failure/distortion at the neck. The edges of LL and SL observed on approach often display linear segments [(*8*), their figure 3], as if the portions of the lobes just out of sight had been sheared off, though this is not entirely clear in the available images. Perhaps these are the outcomes of earlier on-edge, glancing collisions between the lobes (as in Fig. 4A). Alternately, these apparent facets may have been caused by higher-velocity impacts and mass loss, such as have affected the asteroids (*115*), although a heliocentric impact explanation is not consistent with the dearth of large craters on the visible faces of LL and SL, save perhaps for the largest, "Maryland" (*8*).

Table S1.

Estimated YORP coefficients for near-Earth asteroids. From photometric measurements of asteroid rotational accelerations, an empirical, dimensionless torque coefficient *Y* can be estimated from the YORP torque equation $\frac{d\omega}{dt} = \left(\frac{Y}{2\pi\rho R^2}\right)\left(\frac{L_\odot}{4\pi c\bar{a}^2}\right)$, where ω, ρ, and *R* are the spin rate, density, and equivalent radius of the asteroid in question, $L_\odot$ is the solar luminosity, *c* is the speed of light, and $\bar{a} = a_\odot\sqrt[4]{1 - e_\odot^2}$ is the solar-flux-weighted mean heliocentric distance (*77*). In the table *P* is the rotation period, ω/(dω/d*t*) is the spin-rate doubling time, and data sources are indicated. For Itokawa and Bennu the densities are known; for the others 1500 kg m^{-3} is assumed, except for (54509) YORP, (1862) Apollo, and (161989) Cacus, which are likely more monolithic and denser (*116*, *117*, *118*). Note that all these asteroids are spinning up; at present none are spinning down.

Object	**dω/d*t*** (×10^{-8} rad d^{-2})	***P*** (hr)	**$\bar{a}$** (au)	**ω/(dω/d*t*)** (yr)	***R*** (km)	**ρ** (kg m^{-3})	***Y***
54509 YORP (*116*)	350 ± 35	0.203	0.987	5.8×10^5	0.06	2500	0.006
25143 Itokawa (*117*)	3.5 ± 0.4	12.132	1.297	9.7×10^5	0.16	1195	0.0003
1620 Geographos (*75*)	1.2 ± 0.2	5.223	1.206	6.6×10^6	0.98	1500	0.005
1862 Apollo (*117*)	5.5 ± 1.2	16.3	1.338	4.6×10^5	0.75	2500	0.026
3103 Eger (*118*)	1.1 ± 0.5	15.3	1.358	2.5×10^6	0.75	1500	0.003
161989 Cacus (*118*)	1.9 ± 0.3	3.755	1.110	5.8×10^6	0.5	2500	0.003
101955 Bennu (*82*)	4.6 ± 1.8	4.296	1.115	2.1×10^6	0.245	1190	0.0008

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