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A deep dive into the abyss

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The flyby of the Kuiper Belt object Arrokoth provides quick and tantalizing observations

Since 1992, astronomers have unveiled a vast population of solid bodies in orbit beyond Neptune. Known as the Kuiper Belt, this region of the Solar System is a dynamical fossil preserving a record of the planet-formation epoch (*1*). The belt is also a repository of the Solar System's most primordial material and the long-sought nursery from which most short-period comets originate. Most of what we know about the belt was determined using ground-based telescopes. As a result, Kuiper Belt studies have been limited to objects larger than about 100 km because the smaller ones are too faint to easily detect. Now, 5 years after its flyby of the 2000-km-diameter Kuiper Belt object Pluto (*2*), NASA's New Horizons spacecraft has provided the first close-up look at a small, cold classical Kuiper Belt object. Spencer *et al.* (*3*), Grundy *et al.* (*4*), and McKinnon *et al.* (*5*) show one of these objects to be lightly cratered, ultrared, and binary, respectively.

The scientific impact of the Kuiper Belt has been huge, in many ways reshaping our ideas about the formation and evolution of the Solar System. For example, and quite incredibly, Kuiper Belt objects are a thousand times more plentiful than the (much closer and more familiar) main-belt asteroids that orbit between Mars and Jupiter. The Kuiper Belt objects' orbital distribution shows that the planets formed closer to the Sun and then migrated outward, a finding with profound dynamical consequences. The objects themselves are divided into dynamically distinct groups, one of which (the so-called cold classicals) appears to be the most primordial population in the Solar System.

The object that New Horizons flew by is known formally as (486958) Arrokoth (provisional designation 2014 MU_{69}). An earlier working name, "Ultima Thule," was abandoned after the official name was approved. Flyby observations from a 3500-km close-approach distance provide an image scale as small as 33 m/pixel. The most notable feature of Arrokoth is its overall shape, which appears to consist of two spheroidal, but unequal, lobes in contact, like a giant peanut. Combined, they have a volume equal to that of an 18-km-diameter sphere. As noted by Spencer *et al.*, similar binary structures have been observed before in comets and larger Kuiper Belt objects (*6*). Although binarity in sublimating comets exposed to the Sun could result from nonuniform erosion of an initially single body, the frigid environment of the Kuiper Belt minimizes erosion and renders this explanation unlikely.

The most basic inference, then, is that Arrokoth is the product of a collision between two preexisting bodies. The collision must have been gentle because there is no evidence for compressive deformation at the neck connecting the lobes (see the figure). McKinnon *et al.* infer an impact speed comparable to or smaller than the gravitational escape speed, estimated at a few meters per second (*5*). Low-speed accretion is expected in the young protoplanetary disk, where relative motions are damped by friction, first causing loose binaries to form and then driving them to spiral together (*7*). The modern-day Kuiper Belt has no substantial friction, but the protoplanetary disk was much more densely populated, perhaps creating frictional dissipation from collective gravitational effects or from residual protoplanetary gas (*5*). At the same time, Arrokoth's delicate structure is difficult to reconcile with alternate models (*8*) in which Arrokoth-sized Kuiper Belt objects are fragments of larger objects shattered by energetic collisions.

However, impact craters seen lightly sprinkled across the surface of Arrokoth do provide evidence for smaller, higher-speed collisions. The view is limited by the resolution of the data, and by the high-noon illumination of the surface, such that only a few craters are clear. Although the largest crater, 7 km in diameter, is well resolved, all the others are subkilometer, and most are close to the resolution limit of the images. Within the limitations of the data, larger craters show the bowl-shaped morphology that is typical of impact craters on small asteroids with a depth-to-diameter ratio of 0.1 to 0.2 (*3*). Impacts should affect the surfaces of all Kuiper Belt objects more or less equally, and so crater populations on different objects should look basically the same. This should include the moon of Pluto, the most well-known resident of the Kuiper Belt. Curiously, Arrokoth has a steeper crater size distribution and higher crater density at a given size than does the surface of Pluto's moon, Charon. Unlike on Earth's moon, measuring surface age is not possible, and so the crater density cannot be accurately converted into a cratering flux. Such a flux would be extremely useful in assessing the billion-year-scale evolution of the outer Solar System.

The Kuiper Belt is home to the reddest material in the Solar System. This "ultrared matter" is widespread through the belt and is especially abundant in the cold classicals. Ultrared matter is rare or absent interior to the orbit of Saturn, probably because the material is thermodynamically unstable at the higher temperatures found nearer the Sun (*9*). Consistent with this picture, the observations from New Horizons show that the surface of Arrokoth is ultrared. This allows some confirmation of the long-standing suspicion that the color is due to organic materials. Specifically, near-infrared spectra show clear absorption bands due to the alcohol methanol as well as additional unidentified bands. Grundy *et al.* suggest several ways to form methanol, including formation by cosmic-ray irradiation of a simple mixture of water and methane ices (*4*). Although radiation chemistry in the Kuiper Belt is no doubt much more complicated, the latter reaction consumes water, perhaps explaining why New Horizons did not detect it.

New Horizons was a flyby mission. It took more than a decade to advance from concept to launch and another decade to coast to the Kuiper Belt. By contrast, New Horizons acquired the key measurements of Pluto and Arrokoth over encounter periods of just a few days. Having done it once, we can be sure that this is not a particularly efficient or desirable way to investigate the outer Solar System. For future missions, we need to be able to send spacecraft to the Kuiper Belt and keep them there, perhaps by using the gravity of larger Kuiper Belt objects to assist in their capture. A Pluto or Eris orbiter, for example, would allow these intriguing bodies to be studied in stunning geological and geophysical detail. More interesting would be a hopper mission, capable of moving from one Kuiper Belt object to another in much the same way that NASA's Dawn spacecraft moved from Ceres to Vesta using its own ion drive engine. In the Kuiper Belt, where the flux of sunlight is only 0.1% of that on Earth and the distances between objects are truly vast, nuclear rockets are likely necessary to move from place to place with reasonable transit times. Technologically, we could probably do it. Scientific vision and institutional commitment are the extra ingredients needed to make such a mission happen.

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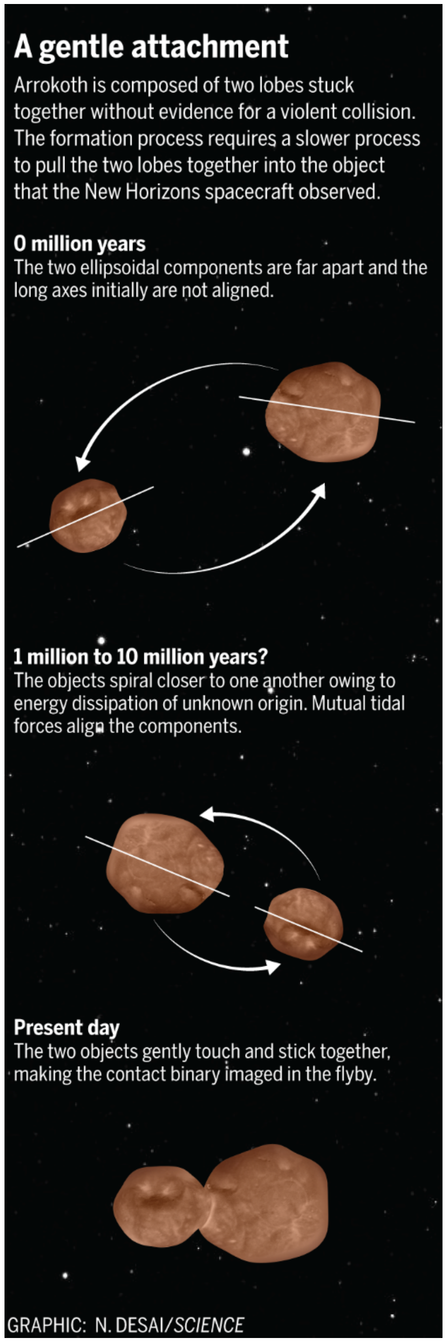
A gentle attachment
Arrokoth is composed of two lobes stuck together without evidence for a violent collision. The formation process requires a slower process to pull the two lobes together into the object that the New Horizons spacecraft observed.
0 million years
The two ellipsoidal components are far apart and the long axes initially are not aligned.
1 million to 10 million years?
The objects spiral closer to one another owing to energy dissipation of unknown origin. Mutual tidal forces align the components.
Present day
The two objects gently touch and stick together, making the contact binary imaged in the flyby.
GRAPHIC: N. DESAI/SCIENCE