STELLAR OCCULTATION RESULTS FOR (486958) 2014MU69: A PATHFINDING EFFORT FOR THE NEW HORIZONS FLYBY. M. W. Buie[1], S. B. Porter[1], P. Tamblyn[1], D. Terrell[1], A. J. Verbiscer[2], B. Keeney[1], A. M. Zangari[1], L. H. Wasserman[3], A. Ocampo[4], S. A. Stern[1] and the New Horizons Occultation Team. [1]Southwest Research Institute, Boulder, CO (buie@boulder.swri.edu), [2]University of Virginia, Charlottesville, VA, [3]Lowell Observatory, Flagstaff, AZ, [4]NASA HQ, Planetary Science Division, Washington, DC.

Introduction: Following its successful encounter with the Pluto system, the New Horizons project entered its extended mission phase. The target, (486958) 2014 MU69 (unofficially nicknamed “Ultima Thule”, referred to here as MU69 for brevity), was discovered just a year before the Pluto encounter. The short time between discovery and encounter on 2019 January 1 presented significant challenges for both navigation to the target and basic characterization needed to help plan the desired observations.

Four stellar occultations were identified – three in 2017 and one in 2018. These events provided an opportunity to study this poorly understood object. With sufficiently dense coverage, a shape and albedo could be determined. Also, a successful event provides high-precision astrometric information that can be used to further refine the orbit of MU69.

Prediction: All predictions were based on the new Gaia DR2 catalog [1,2]. Providing both positions and proper motions led to a far more precise orbit for MU69 and star positions than has every been available before. Without the results from the Gaia mission, these observations would not have been possible.

Equipment: We deployed twenty-two identical systems plus three extras of different but similar capabilities. Most systems used a 40-cm Newtonian telescope. The detector was a QHY174M-GPS that contains an sCMOS detector and integrated GPS receiver for accurate time tagging of images. The readout time was negligible. This camera proved to be a very powerful and robust choice for our purposes.

2017 June 3 occultation: Twelve teams were deployed to Mendoza, Argentina and thirteen to Cape Town, South Africa. Splitting the teams provided some extra protection against weather. The cross-track uncertainty for this event was 44 km. The deployment was based on an 8 km mean spacing, interleaving the sites from the two continents. Despite all teams collecting good data, no occultation was seen. These data were later used for important constraints on the presence of unseen bodies.

2017 July 10 occultation: The ground for this event was largely over the Pacific Ocean. The observations were further hampered by being just 15 degrees from a nearly full moon. Due to these challenges, we did not deploy any ground telescopes for this event. Instead, we used the SOFIA airborne telescope. By this time a large dataset had been collected with the *Hubble Space Telescope* in search of a lightcurve for MU69. The result of that effort doubled the amount of data for the orbit fit and reduced the cross-track error to 14 km.

These observations yielded a very short chord of only ~50 ms or about 1 km. This result was not fully understood until after the July 17 event. This dip was considered as a possible satellite at one point but further analysis shows that it is a grazing event on MU69.

2017 July 17 occultation: The deployment area for this event was Comodoro Rividavia, Argentina. This is on the east coast of Argentina in the southern part of the country. The weather, particularly the wind, was a factor but with local help we built portable wind breaks as well as used trucks to shield the telescopes. The deployment zone was along a major coastal highway and the local government arranged to shut down the road for a couple of hours to let use work alongside the road without interference from lights from vehicles. The teams were spread out in with a mean spacing of 4 km.

Twenty-one of the teams were able to collect useful data. Out of these, five recorded an unambiguous occultation revealing a very complicated shape. The immediate reaction to the shape was the recognition of a contact binary profile. Other explanations were considered such as an irregular shape or a close binary. These options were important influences on the deployment strategy for the next occultation.

2018 August 4 occultation: The final pre-encounter opportunity was observable from Colombia and Senegal. Despite less than perfect weather prospects, the odds of clear weather were good enough to attempt the observations. Mobility was much better in Senegal so twenty-one of the available teams were sent there. Three teams plus extra cameras were sent to Bogota for a backup deployment. The ground-track uncertainty at this time was 13 km but at this point what we didn’t know about MU69 dominated the uncertainties and the deployment strategy. The final inter-site spacing was set to 4 km once again though this covered a very large range of uncertainty for the ground track.

The weather was a large factor and only 3 of the teams were able to collect useful data. One of the teams recorded a clear miss while the other two teams recorded an occultation. This result was not enough to add directly to the shape and orientation constraints (so far) but was very important for providing a location for MU69 at that time for orbit refinement. Also, since the shadow was seen very close to the predicted location, the likelihood of MU69 being a close binary was all but ruled out.

Size and shape: The best shape information came from the July 17 event. When compared to the New Horizons encounter data (see Fig. 1), the agreement is excellent (see also the Stern et al. invited review at this LPSC conference). A full geometric comparison is not yet complete since the apparent separation of the two components is a function of rotation and we do not yet have a sufficiently precise knowledge of the spin period and pole. But, this simple comparison shows the power of such high-density observations on objects of this size. Based on the size from the occultation data, an albedo of 9% was estimated for use in planning the New Horizons imaging sequences.

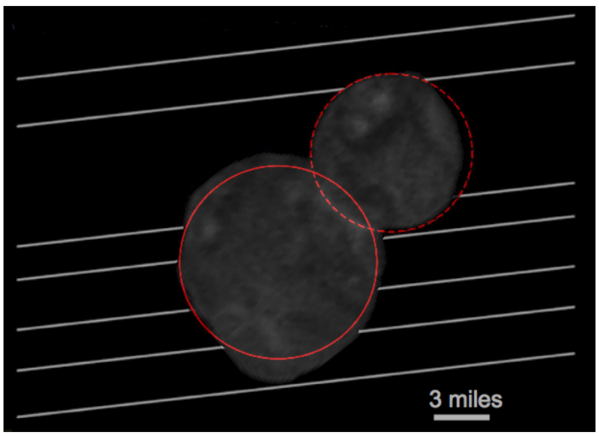

Figure 1: Occultation shape (red circles) derived from fitting the 2017 July 17 data. Overlain on the figure is one of the resolved images from the New Horizons encounter with MU69. The scales are the same between the two data sources. Deviations are evident from sphericity in both the images and the occultation data due to local topography.

Orbit and NH navigation: In addition to shape, the occultation data provided essential constraints and refinements to the orbit estimation for MU69. This orbit was used as an a priori constraint for the optical navigation for the final days leading up to encounter. The occultations, in particular, provided much higher precision measurements of MU69 at two times which very strongly constrained the semi-major axis of the orbit. Without the HST and occultation data, the time of close approach would have been much more poorly constrained and the odds off success for the highest resolution images would have been far lower.

Conclusions: These observations provide a striking example of the power of occultation-based probes of small bodies. This technique, powered by the Gaia star catalog, will revolutionize our ability to see KBO and primordial shapes that can provide key tests of accretion models. These results will be essential to getting shape statistics that are not biased by evolutionary effects such as is the case with comets that we visit in the inner solar system. This technique can be used throughout the solar system and let us tie together their properties across the main asteroid belt, the Jupiter Trojans, and on into the Kuiper Belt.

Acknowledgments: This project was supported by the New Horizons mission and also used data from the *Hubble Space Telescope* and from SOFIA. The observing team numbered more than 100 strong and listing them all here would have left no room for an abstract. Full details of the project and participants will be provided in a full paper yet to come. Success of this project was also due to the incredible support from the countries we visited to make these observations.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. We especially appreciate early access to a sample of the DR2 catalog. Note that the first three events pre-dated the official release and waiting would have meant no data at all.

References: [1] Gaia Collaboration et al. (2016) A&A 595, A1. [2] Gaia Collaboration et al. (2018) Gaia Data Release 2. Summary of the contents and survey properties. ArXiv e-prints. External Links: 1804.09365.