THE MYSTERIOUS MISSING LIGHT CURVE OF (486958) 2014 MU$_{69}$, A BI-LOBATE CONTACT BINARY VISITED BY NEW HORIZONS

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Introduction: (486958) 2014 MU$_{69}$ (hereafter "MU69") was the faintest (R = 26.8) of the three potential targets discovered by the New Horizons KBO search team, but it was the only one reachable with adequate margin with the limited amount of ΔV available onboard the spacecraft. [1] The team sought to characterize this mysterious object through observations of MU69's position, [2] color [3] and rotational light curve. [4] In addition to providing hints about object shape, knowing the rotation period of MU69 would allow for the team to identify the broad side of the object, and possibly tweak the flyby time to maximize the surface area that the spacecraft could image.

Earth-based work: Photometric information for light curve analysis derived from astrometric measurements had been previously found inconclusive (data were taken in June and Oct. 2014, and March, June and Oct. of 2015, 2016, 2017 and 2018). In June 2017, a dedicated light curve campaign observation was undertaken with the Hubble Space Telescope (HST). 119 images were taken over 9.36 days. The campaign also proved inconclusive: owing to the dimness of the object, the data had scatter of roughly 0.15 magnitudes, ruling out an equatorial view of an elongated object with > 1.15 axis ratio. [4]

The HST data were not taken in vain; the nearly-doubling of the number of observations of MU69 permitted excellent predictions of the 2017 July 10 and 2017 July 17 stellar occultations, the latter resulting in a five-chord map of MU69's surface that suggested one of three possibilities: an irregular, elongated object, a contact binary or a binary undergoing mutual events. A second occultation on 2018 August 4 covered one of the lobes. [5]

Approach spacecraft measurements: By August 2018, MU69 was bright enough to be detectable by New Horizons itself. These images were taken by the

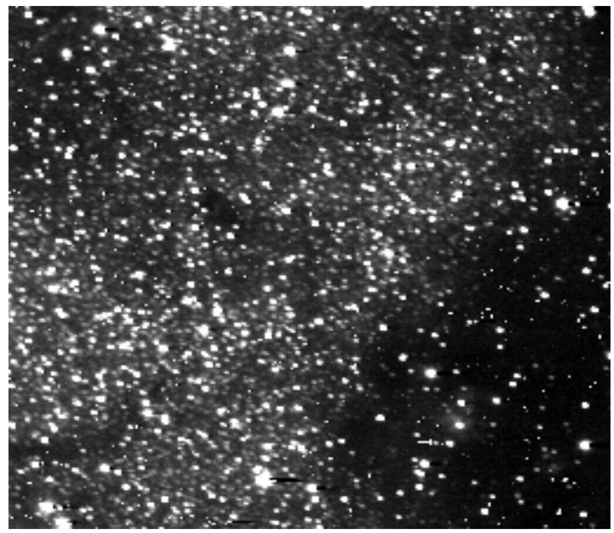

Figure 1: Sample 4x4 LORRI approach image of (486958) 2014 MU$_{69}$. Subtracting out the dense star field made photometric measurement of the KBO rather challenging.

LOng Range Reconnaissance Imager (LORRI) with at first with multiple 30s exposures (an expansion of the maximum 10s exposure time used at Pluto) with 4x4 pixel binning. As MU69 became brighter, this exposure time decreased from 30 to 20 to 10 to 4 to 2 seconds. Images were taken at irregular intervals (usually once per day) with increasing frequency as the encounter approached. These 4x4 images were designed for optical navigation, were taken in immediate succession-- often at similar times each day-- to maximize access to the more-optimally placed DSN stations, owing to the low bit rate at 44 AU. In addition to the regular OpNav images taken throughout approach, New Horizons took five series of hazard observations, groups of 110, 120, 61, 52, and 40 images taken over the course of 70, 77, 49, 37 and 24 minutes at maximum, designed to be combined to create a deep stack suitable for searching for moons and rings. [6]

These 4x4 images were suitable for photometry up until Dec. 30. These images were difficult to work with because of the dense stellar background due to MU69's galactic latitude of -2.6° as seen from the spacecraft (see Figure 1). The general solution was to subtract a template image of the field that LORRI had observed the previous year, when MU69 was present, but below the detection threshold, and stack the subtracted images to create a single image from each visit. Two team members were responsible for creating an independent astrometric plate solution that five hazard team members would use for reporting photometry and astrometry of MU69. One team member provided photometry and astrometry from both plate solutions, for a total of six photometric measurements for each observation.

Eight days before encounter, 1x1 LORRI navigation images at 0.5s exposure were taken of MU69 up until 2 days before encounter, when 0.15s 1x1 science imaging began.

Photometric data were searched for periodic variations using multiple period-fitting techniques throughout the approach. Unfortunately, owing to the systematics caused by a moving object through imperfect background star subtraction, and other causes not yet determined, the photometric measurements from the six independent data sets were not consistent with each other, to the degree that a search for a period produced no strong results, nor any that formed a coherent folding pattern in the data. The best periods found only matched as many as half the independent data sets, and did not persist as new data were incorporated during the approach period. Ultimately, it was realized that a period would only be found when MU69 became resolved, despite the amount of data downlinked.

Resolved encounter images: MU69 only became resolved in the Dec. 30 and Dec. 31 LORRI 1x1 failsafe images as a bi-lobate contact binary. From the visible rotation of the lobes, an approximate period of 15+/-1 hours could be derived. Three well-resolved 1x1 LORRI images have been downlinked post-encounter at the time of this writing. These images were used to create clay model of MU69 [7] that was scanned and used to derive a preliminary, approximate solution for the rotation axis, pointing at J2000 RA 300°, Dec -21°. [8] These results suggest that the negative pole was inclined 23° from pole-on as seen from the spacecraft, and the negative pole was inclined 14° from pole-on as seen from Earth. Using the pole inclination and the radii of the two lobes (9.73 km and 7.12 km [9]), an analytic model of the two lobes as flat disks was created to approximate the light curve that should have been seen on approach. The predicted 1.3% drop from maximum light (0.014 mag) falls well within the systematic scatter that spans 0.15 mag in the LORRI approach data and HST datasets.

Pole-on contact binaries have lower light curve amplitudes than ellipsoids of similar shapes and inclinations. [10] An ellipsoidal model with similar minima and maxima to our contact binary (semi-axes of 14.94 km, 9.73 km and 9.73 km), also inclined 23°, would have an drop of 4.5% from maximum light (0.05 mag), also inside the systematic scatter reported. Figure 2 shows these two models superimposed on top of the six sets of photometric measurements. Neither searching the light curve data for the best fit period between 14h and 16h nor forcing a fit of 15.0 h produces a coherent light curve. The low-amplitude light curve may have influenced MU69's discovery, as this dimmest object is near its maximum light, barely above detection thresholds. [11]

References:

[1] Buie M. W. et al (2019) *in prep*. [2] Porter S. B., et al (2019) *AJ,* 156, 20. [3] Benecchi S. D. et al (2019) *Icarus,* revisions returned. [4] Benecchi S. D. (2019), *Icarus,* under revision. [5] Buie M. W. et al, this meeting. [6] Spencer, J.R. et al, this meeting. [7], Kinczyk, M. J. et al, this meeting. [8] Porter, S.B. et al, this meeting. [9] Bierson, C. J., this meeting. [10] Showalter, et al, this meeting. [11] Parker, A. H., et al, this meeting.

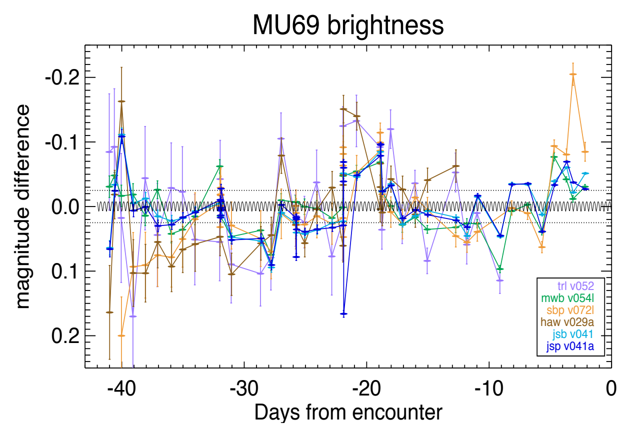

Figure 2: LORRI 4x4 photometric measurements of (486958) 2014 MU$_{69}$ by six independent methods, all normalized to have the same mean magnitude. A model contact binary light curve using the preliminary pole (23°) and period (15h) has been superimposed upon the data. Dashed lines indicate the amplitude of a model ellipsoidal object with the same edge on maxima, edge on minima, and inclination. The noise of the MU69 4x4 measurements precluded the derivation of any period from these results.