GRAVITY, ROTATION, AND HILL SLOPES OF 2014 MU69. J. T. Keane[1], C. J. Bierson[2], C. M. Lisse[3], M. W. Showalter[4], J. A. Stansberry[5], O. M. Umurhan[6], J. M. Moore[6], W. B. McKinnon[7], A. J. Verbiscer[8], J. W. Parker[9], C. B. Olkin[9], H. A. Weaver[3], J. R. Spencer[9], S. A. Stern[9], and the New Horizons Geology, Geophysics, and Imaging (GGI) Team. [1]California Institute of Technology (Pasadena, CA 91125, USA, jkeane@caltech.edu), [2]University of California, Santa Cruz, (Santa Cruz, CA 95064, USA), [3]Johns Hopkins University Applied Physics Laboratory (Laurel, MD 20723, USA), [4]SETI Institute (Mountain View, CA 94043, USA), [5]Space Telescope Science Institute (3700 San Martin Drive, Baltimore, MD 21218, USA), [6]NASA Ames Research Center (Moffett Field, CA 94035, USA), [7]Washington University in St. Louis (St. Louis, MO, USA), [8]University of Virginia (Charlottesville, VA 22904, USA), [9]Southwest Research Institute (1050 Walnut St., Suite 300, Boulder, CO 80302).

Introduction: On 1 January 2019, NASA's New Horizons spacecraft performed the first flyby of a small Kuiper Belt Object, (486958) 2014 MU_{69} (henceforth "MU69"). New Horizons revealed a fascinating bi-lobed contact binary (Fig. 1A), that likely records some of the earliest epochs of solar system formation [1].

The unique contact binary structure of MU69 is expected to result in an interesting, yet unintuitive, gravity field and rotation state. Gravity and rotation are fundamental characteristics of small bodies that control a wide array of geologic processes—from mass-wasting (e.g., landslides, creep), to internal stresses and tectonics. In this work, I present a collection of models for the gravity field, rotation, and surface hill slopes of MU69. I find that several important features on this small body are related to surface slopes, and that the hypothesized formation scenario of MU69 may leave records in the present-day geology.

Shape and Spin of MU69: At the time of writing, the simplest shape model for MU69 is two grazing spheres, with radii of 9.73±0.02 km and 7.12±0.02 km, respectively [2]. The geometry of the "neck" between the two lobes is currently uncertain, as is the higher-order shape of either individual lobe. A preliminary clay shape model was constructed by hand, and used for a combination of scientific analyses, and outreach and public engagement [3]. In this abstract, I focus on analysis of the simpler two-spheres model. This will be revised as more data is downlinked from New Horizons, meriting more sophisticated shape models [4, 5].

The rotation rate of MU69 was measured by analysis of distant approach images, which only barely resolved MU69. The rotation rate is presently estimated to be 15±1 hours. [6, 7]. I presume that MU69 is in a lowest-energy, principal-axis rotation state, with the rotation axis aligned with the maximum principal axis of inertia, going through the center of mass.

Gravity, Rotation, and Hill Slopes of MU69: I calculated the surface gravity and centrifugal force vectors across the surface of both spheres, using classical analytic formalisms. I assumed a uniform bulk density for both lobes of 500 kg/m^3, consistent with the densities of other primitive objects, like comet 67P/Churyumov-Gerasimenko [8, 9]. The surface slopes were calculated by finding the angle between the total force vectors and surface normal at every point on either sphere.

Fig. 1B–C shows the predicted normal surface gravity and surface slopes across the surface of MU69, in approximately the same geometry as the initial New Horizons observations. The mean radial surface gravity is ~1.3 and ~1.0 mm/s^2 on the large and small lobes, respectively.

Correlations Between Predicted Hill Slopes and Surface Features on MU69: Perhaps the most striking surface feature on MU69 is its anomalously bright

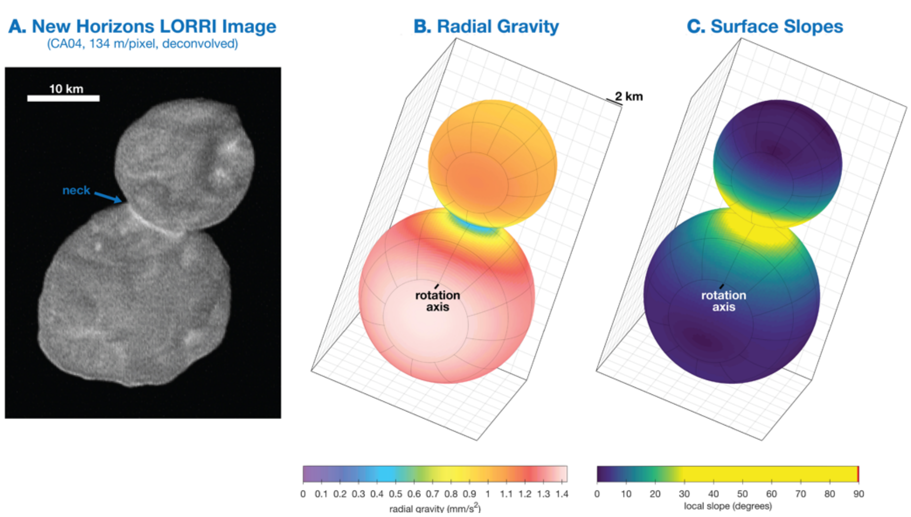

***Fig. 1. A**, New Horizons image of MU69. **B,** predicted radial gravity for MU69. Gravity is measured positive downward. **C,** predicted surface slopes for MU69. Shallow slopes are in blue, and steep slopes are in green. Unstable hillslopes (above the typical 30° angle of repose) are in yellow. Regions in red are effectively overhangs (slopes >90°), and (strengthless) material would fly off of the surface. The models (b–c) are oriented in approximately the same geometry as the New Horizons image.*

"neck" (Fig. 1A). Fig. 1C clearly shows that this region is associated with the steepest slopes on MU69. This is because points on the surface of each lobe near the neck are more strongly perturbed by the gravity of the opposite lobe. The neck is a gravitational potential low, meaning that hillslopes point downward into the neck. This is qualitatively similar to the inferred slopes on 67P/Churyumov-Gerasimenko [8].

While the neck is associated with steep slopes, it is uncertain if the bright material in the neck is on steep slopes or not. Regolith on steep slopes will tend to slump into the neck region, filling it in. At present, it is unclear if the bright material is associated with slumped, neck-filling material (which would have shallow slopes, as the slumped material would approximately fill an equipotential surface), or if the bright material is associated with the scarps on either side of the neck (which would have steep slopes). Alternatively, it is possible that the bright material is not a direct consequence of steep hillslope processes, but instead resulted from the unique thermal/radiation environment near the neck, or from processes that occurred during the formation of the contact binary itself. Forthcoming New Horizons images are expected to provide much higher resolution imagery of the neck region, and answer some of these questions.

Early, Faster Spin of MU69: If MU69 initially formed as a separated binary [1, 10], then it likely formed with an initially faster rotation rate. The orbital period for the two lobes, orbiting their common center of mass just before merger, is ~9 hours (assuming 500 kg/m^3 densities). The transition from orbiting binary to contact binary will result in significant changes in the surface slopes on the two bodies, perhaps resulting in mass wasting with a characteristic geometry.

Fig. 2 shows how the hill slopes evolve as MU69 evolves from a separated, orbiting binary (Fig. 2A–B), to a slower spinning contact binary (Fig. 2C–D). As the two bodies spiral closer together, material on the "nearside" of both bodies will slump towards what will become the future neck region. Prior, and just-after merger, the hill slopes are also steep (>25°) on the "farside" of the smaller lobe, which may lead to mass-wasting towards the far end of MU69 (Fig. 2C). Eventually MU69 slows to its current 15 hour rotation period, where the only remaining steep slopes are near the neck (Fig. 2D). It is important to note that the present-day neck is expected to be asymmetric; the steeper slopes are on the smaller lobe of MU69.

It is unclear how MU69 lost angular momentum after it became a contact binary—and this is a topic of active research. Alternatively, MU69 would not need to lose any angular momentum if it is presently spinning at its mutual orbit velocity. This would require an extremely low density of ~180 kg/m^3.

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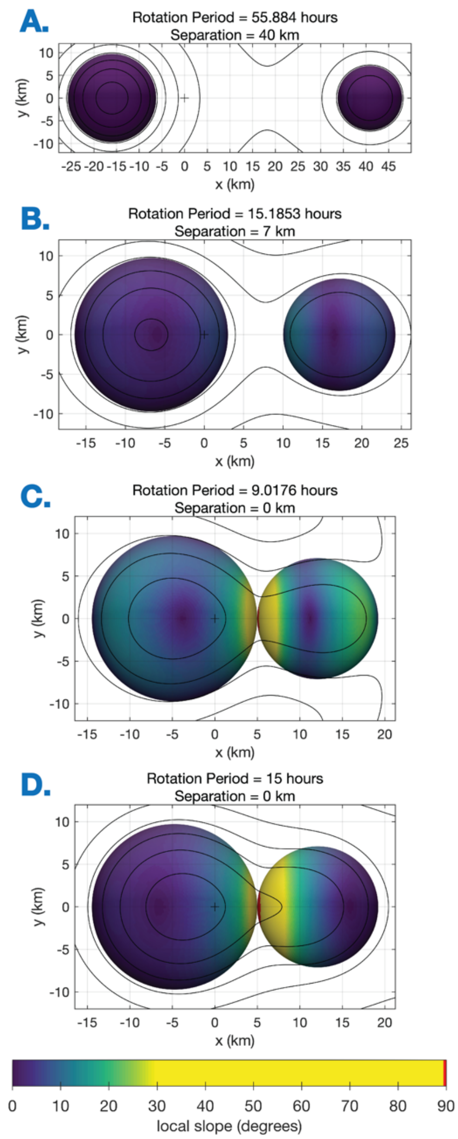

Fig. 2. Predicted hill slopes on MU69 as it transitions from a separated binary (A, B) to a contact binary (C) with the present spin period (D). Assuming a density of 500 kg/m^3, the two objects touch at a rotation period of 9 hours (C). Panels are shown from along the rotation axis (z-axis). Colors indicate hill slopes on the surface of MU69, as in Fig. 1. Contours are equipotential curves, evaluated at the mid-plane (z=0).