OVERVIEW OF INITIAL RESULTS FROM THE RECONNAISANCE FLYBY OF A KUIPER BELT PLANETESIMAL: 2014 MU$_{69}$ S.A. Stern[1], J.R. Spencer[1], H.A. Weaver[2], C.B. Olkin[1], J.M. Moore[3], W. Grundy[4], R. Gladstone[5], W.B. McKinnon[6], D.P. Cruikshank[3], L.A. Young[1], H.A. Elliott[5], A.J. Verbiscer[7], J. Parker[1], and the New Horizons Team. [1]Southwest Research Institute, 1050 Walnut St. Suite 300, Boulder, CO 80302 (astern@boulder.swri.edu), [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, [3]NASA Ames Research Center, Moffett Field, CA 94035. [4]Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, [5]Southwest Research Institute, 6220 Culebra Road, San Antonio, TX, 78238, [6]Dept. Earth and Planetary Sciences, Washington University, St. Louis, MO 63130. [7]Department of Astronomy, University of Virginia, Charlottesville, VA 22904.

Introduction: The centerpiece objective of NASA's New Horizons first Kuiper Extended Mission (KEM-1) was the close flyby of the Kuiper Belt Object (KBO) 2014 MU$_{69}$, nicknamed Ultima Thule [1]. On 1 Jan 2019 this flyby culminated, making the first close observations of a small KBO. Final pre-flyby trajectory predictions indicated the spacecraft would approach to within 3,500±30 km of MU$_{69}$ at 05:33±0:01 UT.

Here we summarize the earliest results obtained from that successful flyby. At the time of this abstract's submission, only 4 days of data downlink from the flyby were available; well over an order of magnitude more data will be downlinked by the time of this LPSC meeting in 2019 March. Therefore many additional results not available at the time of this abstract submission will be presented in this review talk.

Objectives: 2014 MU$_{69}$ was discovered by members of the New Horizons team using the Hubble Space Telescope in 2014 [2]. MU69's orbit identifies it as a cold classical KBO. This means it has probably been resident at its current heliocentric distance (43 AU) and cold conditions for the past ~4.5 Gyrs. This, combined with its small size which prevents it from maintaining a strong internal geologic engine to the present, combine to make MU69 the most primitive body ever studied by any planetary spacecraft.

Other than its orbital parameters and brightness, the only information known about Ultima Thule prior to observations by New Horizons were its red color [3], an approximate size (25-30 km diameter) and shape profile at the time of a 17 July 2017 stellar occultation [2], and a visible albedo estimate (~0.1) also from this occultation-measured size [2].

Key objectives of the flyby of MU69 [1] were: to obtain panchromatic imaging, visible/near-IR wavelength four-color imaging, and stereo imaging of MU69's surface; to map Ultima Thule's surface composition across the 1.25-2.5 μm IR; and to make sensitive searches for both rings and satellites orbiting Ultima Thule and any gas or particulate coma. Secondary objectives included day and night side disk-integrated average brightness temperature measurements at a wavelength of 4 cm, an attempt to measure Ultima Thule's bistatic radar reflectivity at 4 cm, a search for dust impacts onto the spacecraft near Ultima Thule, and a search for detectable plasma interactions with the solar wind. Most of these objectives require data not yet on Earth before they can be written about. However, some data, comprising well under 1% of the total stored aboard New Horizons, is presently on the ground. We report on those data here.

Initial Results. New Horizons has revealed MU69 to be a bi-lobate contact binary that appears to have merged at low speed. In addition to being the most primitive solar system object ever to be explored in situ by any spacecraft, MU69 thus also becomes the first primordial contact binary. The appearance and contact binary nature of this object is consistent with it being a relic planetesimal possibly created by pebble accretion. How MU69's two lobes merged, how gently, and how much angular momentum was lost prior to contact are puzzles to be solved as more data are returned and detailed modeling can be undertaken.

MU69's panchromatic and color appearances are shown in Figures 1 and 2, respectively.

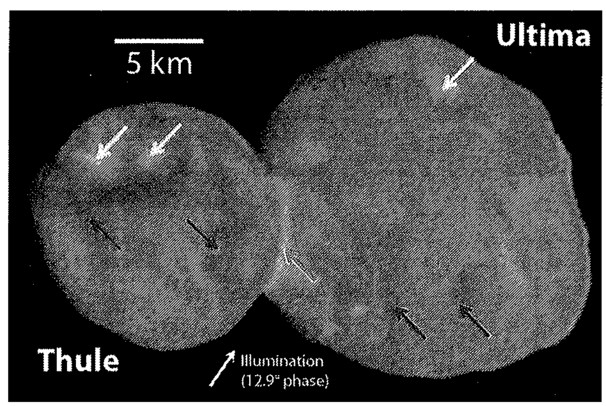

Figure 1: Ultima Thule as seen by the LORRI imager in the close approach CA04 observation (140 m/pixel), including relatively bright circular patches a few km wide (yellow arrows), darker regions up to several km wide (red arrows), a bright, cylindrically symmetric neck (blue arrow), and quasi-linear and arcuate bright features; note also the mottled appearance.

The two lobes of MU69 have very similar, quasi-spherical shape profiles in the available imaging. This

* Some feature names mentioned in this paper are now formalized while others are informal

near sphericity is likely an important clue to their accretional mechanism. Ultima Thule's overall major axis length is 31.7±0.5 km.

For the purposes of discussion, MU69's larger and smaller lobes have been informally designated "Ultima" and "Thule," respectively, by the New Horizons team. Ultima and Thule have best-fit measured diameters of ~19.5 and ~14.2 km, respectively with errors of only a few percent at this time. This, combined with its low amplitude lightcurve determined by New Horizons, suggests that the two lobes have ~2.6:1 volume, and perhaps, mass ratios.

Ultima Thule's rotation period has been measured by New Horizons at 15±1 hours. How it slowed to this relatively long period after merging is another puzzle to be solved.

Although a mottled appearance and limb topography (amplitudes >1 km for Ultima and ~0.5 km for Thule) was resolved on each lobe, geological features are not clearly identifiable in the currently available images, which have only a limited range of low (11-13°) solar phase angles. However, the significant limb topography variations detected suggest a mechanically strong "crustal zone" and/or bulk interior, perhaps composed of some combination of H_2O-ice, CO_2-ice, other ices, and refractory organics/rock.

Although the two lobes of Ultima Thule have closely similar reflectivities, significant albedo variations of 0.06-0.14 are seen on both lobes. The average I/F for the object as seen in Figure 1 is 0.09. Initial analysis reveals that this average albedo is similar to other cold classical KBOs. The most prominent albedo feature is a narrow (<300 m tall) bright, cylindrically symmetric neck where the lobes Ultima and Thule are joined. The origin of this remarkable feature is unclear; either endogenic (fine particle accumulation) and/or exogenic (lobe merger) possibilities may be the cause.

Ultima Thule's overall color displays a red slope of +24.3% per 1000 Å at 5500 Å. Additionally, New Horizons found 1.25-2.5 μm near-infrared I/F varies between 0.17 and 0.19.

Little significant color variegation across either lobe has been detected as of this writing; however, the brighter neck region at the interface of the two lobes is slightly less red than the bulk color. Initial analysis reveals that Ultima Thule's color is similar to other cold classical KBOs (see also [3] with lower SNR HST color measurement than New Horizons). In comparing our Ultima Thule observations to Nix, we do not yet see strong evidence for the 2.0 μm H_2O-ice band, and therefore the abundance of H_2O-ice on the surface is likely to be much less than observed by New Horizons on Pluto's satellites [4].

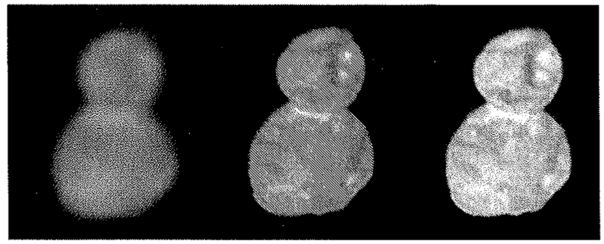

Figure 2: Left to right: Enhanced color image at 1.5 km/pixel resolution, panchromatic image at 140 m/pixel resolution, and enhanced color overlaid on the panchromatic image.

As expected, we found no evidence for a gas coma in initial inspections of UV airglow and solar appulse coma absorption datasets collected by the UV spectrograph on New Horizons, though the majority of those data are still to be downlinked. As also expected, no solar wind interaction or emitted pickup ions were detected in initial data analyses of the New Horizons plasma and charged particle spectrometer instruments, though the majority of those data are also still to be downlinked.

Regarding dust near Ultima Thule, New Horizons saw no evidence down to I/F~$5x10^{-7}$ in imaging available by 4 Jan 2019. In addition, zero impacts onto the New Horizons dust counter were detected inside MU69's Hill sphere. And no satellites were detected down to 1.5 km diameter (under the assumption of an Ultima Thule-like reflectivity) outside of 1000 km from Ultima Thule. A search for closer rings or satellites has not yet been performed.

References. [1] Stern, S. A., Weaver, H.A, Spencer, J.R., and Elliot, H.A. (2018), *Space Science Reviews 214*, 76-99. [2] Buie, M.W. et al. (2018), DPS Meeting #50, id.509.06. [3], Benecchi, S., et al. (2019), Icarus, in press. [4] Cook, J., et al. (2018), Icarus, 315, 30-45.

Acknowledgements. This work was funded by NASA. We thank NASA, the Deep Space Network, JPL, KinetX Aerospace, the entire present and past New Horizons team, and the Gaia and HST missions for making the flyby of MU69 successful.

al Mechanics

ssuming that MU69 was discovered at perihelion and that it has an orbital eccentricity of 0.042, what will be its aphelion distance? (5 points)

2. What is MU69's orbital period? (3 points)

3. *New Horizons* flew by MU69 with a relative velocity of 14.44 km/s.

   a) Using the estimated closest approach distance cited in the paper, calculate the reduction in velocity required to have the spacecraft be captured into a circular orbit by MU69. For simplicity you may ignore MU69's orbital motion around the Sun. Estimate/approximate any other properties of MU69 and/or *New Horizons* needed to do this calculation. (5 points)

   b) This maneuver is similar to the one used to place *OSIRIS-REx* in orbit around Bennu, in which the spacecraft slowed by 530 m/s to achieve an approach speed of 0.2 m/s prior to orbit insertion. Compare your result in (a) to the *OSIRIS-REx* situation and discuss why would such a maneuver have been impractical for *New Horizons*. [If you were stuck on 3a and did not get a numerical answer, provide a qualitative answer here.] (3 points)

Observations

4. In the Objectives section the authors state that the visible albedo of MU69 was estimated from its occultation-derived size. Explain *in qualitative terms* the relationship between these two quantities. You do not need to provide a formula; rather, discuss the dependency between these two quantities and how knowing one could inform the other. You may ignore the shape of MU69 in your discussion. (3 points)

5. Use the energy balance equation and other information given in the paper to determine the equilibrium temperature of MU69. Estimate values for any other parameters you need that are not provided. (5 points)

6. Figure 1 indicates that the CA04 observation of MU69 was made at a phase angle of 12.9°. Define what is meant by the *phase angle* and draw a diagram with the locations of the relevant bodies to produce such a phase angle. **After** the closest approach, how did the phase angle change, and what value did it approach? (4 points)

Contact Binaries

7. MU69 is described as a *contact binary*. Imagine that its major axis is aligned with the x-axis, and its rotation axis is aligned with the y-axis (in the plane of the page and straight up, as depicted in Figure 1; note that the green arrow representing the rotation

January 1

N. Chanover

CUME EXAM # 430

This exam is worth 64 points. It is based on the accompanying abstract for the Lunar Planetary Science Conference that will be held in March 2019: Stern *et al.* (2019), "Overv of initial results from the reconnaissance flyby of a Kuiper Belt planetesimal: 2014 MU_{69} A grade of 70% or higher is expected to be a passing grade. **You may use a calculator but only for algebraic and trigonometric types of calculations – you may NOT use a calculator to store formulae, constants, etc.**

Things You Might Need to Know

Symbol	Value in cgs	Value in SI
c	2.998×10^{10} cm s^{-1}	2.998×10^{8} m s^{-1}
G	6.674×10^{-8} dyn cm^{2} g^{-2}	6.674×10^{-11} N m^{2} kg^{-2}
k	1.3806×10^{-16} erg K^{-1}	1.3806×10^{-23} J K^{-1}
σ	5.670×10^{-5} erg cm^{-2} K^{-4} s^{-1}	5.670×10^{-8} W m^{-2} K^{-4}
1 AU	1.496×10^{13} cm	1.496×10^{11} m
$M_\odot$	1.9891×10^{33} g	1.9891×10^{30} kg
$R_\odot$	6.955×10^{10} cm	6.955×10^{8} m
$L_\odot$	3.827×10^{33} erg s^{-1}	3.827×10^{26} W

Additional Instructions

- Start each question on a new page and then staple your packet of pages together at the end. Put your name on every page.
- Write legibly! If I cannot read your writing, you likely will not receive as much credit as you deserve because I won't understand what you are trying to convey.
- The topics of the questions and their respective point values are as follows:
  Orbital Mechanics (#1-3): 16 points
  Observations (#4-6): 12 points
  Contact Binaries (#7-9): 25 points
  The MU69 Environment (#10): 11 points

axis was added by me for the purpose of this discussion – it is not necessarily accurate).

a) Draw the appearance of MU69 for at least four different points in its rotation. The geometry in Figure 1 can be considered t_0; draw that, plus what the object looks like at t_1, t_2, t_3, and t_4, where t_1 is one fourth of the rotational period ($\frac{1}{4}$ P_{rot}), $t_2 = \frac{1}{2}$ P_{rot}, $t_3 = \frac{3}{4}$ P_{rot}, and $t_4 = P_{rot}$. (5 points)

b) Below that, draw the light curve of MU69 that you would expect to see from Earth, with rotational phase (going from 0 to 1) on the x-axis and brightness (arbitrary units) on the y-axis. Try to align your light curve directly below the drawings you made for (a) so that we can see how the observing geometry relates to the observed light curve. (5 points)

c) Now make a similar set of diagrams for a system (again, observed from Earth) where the diameter of the primary is several orders of magnitude larger than the secondary and the two masses are separated by 100 primary radii, so now it is an eclipsing binary (same orbital geometry) rather than a contact binary. (5 points)

d) Describe qualitatively how the two light curves you drew should be different, and why. (3 points)

8. One puzzle revealed during the *New Horizons* flyby of MU69 is that the light curve measured by the spacecraft had a very small amplitude. What could cause this, given that the shape of MU69 was determined to be bi-lobate from Earth-based occultation measurements made in the summer of 2017? (3 points)

9. Provide a qualitative discussion of how the contact binary Ultima Thule could have formed. Given your answer, why do you think we don't we see many contact binaries in the solar system? (4 points)

The MU69 Environment

10. In the final paragraph the authors state that no dust impacts were detected inside MU69's Hill sphere.

a) Describe in words what a Hill sphere is. (3 points)

b) Calculate the size of MU69's Hill sphere, stating whatever assumptions you made in order to do the calculation. (5 points)

c) In the final paragraph the authors also state that "no satellites were detected down to 1.5 km diameter (under the assumption of an Ultima Thule-like reflectivity) outside of 1000 km from Ultima Thule." How significant do you think this result is? (3 points)

N. Chanover

January 19, 2019

CUME EXAM # 430 WITH SOLUTIONS

This exam is worth 64 points. It is based on the accompanying abstract for the Lunar and Planetary Science Conference that will be held in March 2019: Stern *et al.* (2019), "Overview of initial results from the reconnaissance flyby of a Kuiper Belt planetesimal: 2014 MU_{69}." A grade of 70% or higher is expected to be a passing grade. **You may use a calculator, but only for algebraic and trigonometric types of calculations – you may NOT use a calculator to store formulae, constants, etc.**

Things You Might Need to Know

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Additional Instructions

- Start each question on a new page and then staple your packet of pages together at the end. Put your name on every page.
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  Orbital Mechanics (#1-3): 16 points
  Observations (#4-6): 12 points
  Contact Binaries (#7-9): 25 points
  The MU69 Environment (#10): 11 points

Orbital Mechanics

1. **Assuming that MU69 was discovered at perihelion and that it has an orbital eccentricity of 0.042, what will be its aphelion distance? (5 points)**

   Use the general orbit equation to solve for a and then for r_{ap}:

   $$r = \frac{a(1-e^2)}{1+ecos\theta} \tag{1}$$

   At perihelion, $\theta = 0°$ and r_{peri} is 43 AU (from paper) $\rightarrow a = 44.885$ AU. Then use Eq. (1) again, knowing a and $\theta = 180°$ at aphelion to solve for r_{ap}. Should get a value of 46.77 AU.

2. **What is MU69's orbital period? (3 points)**

   Use the simple version of Kepler's Third Law ($p^2 = a^3$) and the value for a that you found in #1. Solving for p, you should get 300.7 years.

3. *New Horizons* **flew by MU69 with a relative velocity of 14.44 km/s.**

   a) Using the estimated closest approach distance cited in the paper, calculate the reduction in velocity required to have the spacecraft be captured into a circular orbit by MU69. For simplicity you may ignore MU69's orbital motion around the Sun. Estimate/approximate any other properties of MU69 and/or *New Horizons* **needed to do this calculation. (5 points)**

   Here we want to balance the gravitational force that MU69 exerts on *New Horizons* with the centripetal force that spacecraft would feel if it were in a circular orbit around MU69, and solve for v:

   $$\frac{GMm}{r^2} = \frac{mv^2}{r} \rightarrow v = \sqrt{\frac{GM}{r}} \tag{2}$$

   M is the mass of MU69 and r is the closest approach distance (3,500 km from the paper). Estimate the mass by multiplying the volume, which you can determine by its size (it's OK to approximate it as a sphere) by a representative density for outer solar system objects. We can assume $\rho = 1.5$ g/cm^3 or 1,500 km/m^3. If we assume that the object is spherical in shape with a radius of 10 km, then the volume of MU69 would be 4.19×10^{12} m^3, and hence its mass is 6.28×10^{15} kg. Using these values, we can solve for v to be 0.35 m/s. Thus, *New Horizons* would have had to slow down by (14.44 - 0.35×10^{-3} km/s) in order to be captured into orbit by MU69. [This is a LOT!!!!!].

   Note that using a Hohmann Transfer Orbit would not be appropriate in this case. An HTO is used to move between two orbits around the same body (usually the Sun, in the cases we looked at in ASTR 620). Here you were asked to determine what the orbital velocity of *New Horizons* would be at some distance from MU69, and compare that to the velocity that the spacecraft actually had as it flew by.

b) This maneuver is similar to the one used to place *OSIRIS-REx* in orbit around Bennu, in which the spacecraft slowed by 530 m/s to achieve an approach speed of 0.2 m/s prior to orbit insertion. Compare your result in (a) to the *OSIRIS-REx* situation and discuss why such a maneuver would have been impractical for *New Horizons*. [If you were stuck on 3a and did not get a numerical answer, provide a qualitative answer here.] (3 points)

The required reduction in speed by *New Horizons* is several orders of magnitude larger than what was required for *OSIRIS-REx* in order for it to be moving slowly enough that it could be captured into orbit around Bennu. This is simply impractical; it would have required a ridiculous amount of fuel to achieve such a Δv.

<u>Observations</u>

4. **In the Objectives section the authors state that the visible albedo of MU69 was estimated from its occultation-derived size. Explain *in qualitative terms* the relationship between these two quantities. You do not need to provide a formula; rather, discuss the dependency between these two quantities and how knowing one could inform the other. You may ignore the shape of MU69 in your discussion. (3 points)**

   The albedo of an object is a measure of its reflectivity. It can depend on surface properties such as composition and porosity of the regolith, and it can also depend on geometric properties such as phase angle and rotational modulation. There is an empirical relationship between albedo, size, and absolute magnitude of small bodies wherein the albedo is inversely proportional to the area (size^2) of the object. You were not expected to know about this relationship, but you should address the fact that a large object that is less reflective (lower albedo) could end up looking the same in terms of overall brightness (magnitude) as a smaller more reflective object.

5. **Use the energy balance equation and other information given in the paper to determine the equilibrium temperature of MU69. Estimate values for any other parameters you need that are not provided. (5 points)**

   The energy balance equation ($E_{in} = E_{out}$) states that

$$\varepsilon 4\pi R^2 \sigma T_{eq}^4 = (1-A)\pi R^2(\pi F_\odot), \tag{3}$$

   where R is the radius of MU69, ε is the emissivity of the object, A is its albedo, and $\pi F_\odot$ is the solar flux at the target, which can be rewritten as $L_\odot/4\pi d^2$ where d is the object's heliocentric distance.

I tend to do these calculations relative to Earth because I find it easier to work with the solar constant (1368 W/m^2) and in distance units of AU. In that case

$$\frac{(1-A)(solar\ flux\ at\ Earth)}{(distance\ in\ AU)^2} = \varepsilon 4 \sigma T_{eq}^4 \tag{4}$$

Assuming an emissivity of 1 and an albedo of 0.1 and plugging in the other constants, I get $T_{eq} = 42.4$ K.

6. **Figure 1 indicates that the CA04 observation of MU69 was made at a phase angle of 12.9°. Define what is meant by the *phase angle* and draw a diagram with the locations of the relevant bodies to produce such a phase angle. After the closest approach, how did the phase angle change, and what value did it approach? (4 points)**

   The phase angle is the Sun-Target-Observer angle (see below; in that case the observer is at Earth, although they do not have to be!). If the phase angle is 0°, then the Sun is directly behind the observer and the object being observed is fully illuminated.

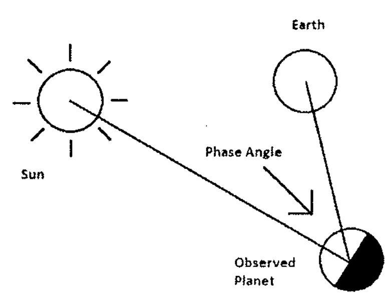

Figure 1: From http://upload.wikimedia.org/wikipedia/commons/1/10/Phase_Angle_3.jpg.

   After closest approach, the phase angle *increased* and eventually approached 180°.

Contact Binaries

7. **MU69 is described as a *contact binary*. Imagine that its major axis is aligned with the x-axis, and its rotation axis is aligned with the y-axis (in the plane of the page and straight up, as depicted in Figure 1; note that the green arrow representing the rotation axis was added by me for the purpose of this discussion – it is not necessarily accurate).**

a) **Draw the appearance of MU69 for at least four different points in its rotation. The geometry in Figure 1 can be considered t_0; draw that, plus what the object looks like at t_1, t_2, t_3, and t_4, where t_1 is one fourth of the rotational period ($\frac{1}{4}$ P_{rot}), $t_2 = \frac{1}{2}$ P_{rot}, $t_3 = \frac{3}{4}$ P_{rot}, and $t_4 = P_{rot}$. (5 points)**

The below diagram is what I had in mind for this question.

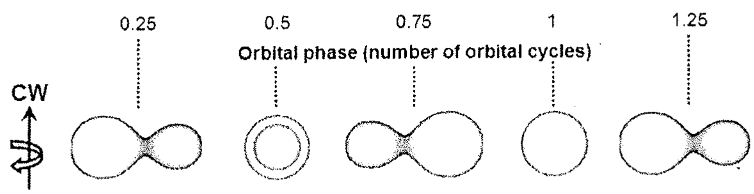

Figure 2: From http://cronodon.com/SpaceTech/BinaryStar.html

b) **Below that, draw the light curve of MU69 that you would expect to see from Earth, with rotational phase (going from 0 to 1) on the x-axis and brightness (arbitrary units) on the y-axis. Try to align your light curve directly below the drawings you made for (a) so that we can see how the observing geometry relates to the observed light curve. (5 points)**

The below diagram is what I had in mind for this question (in this case the light curve is above the various drawings rather than below).

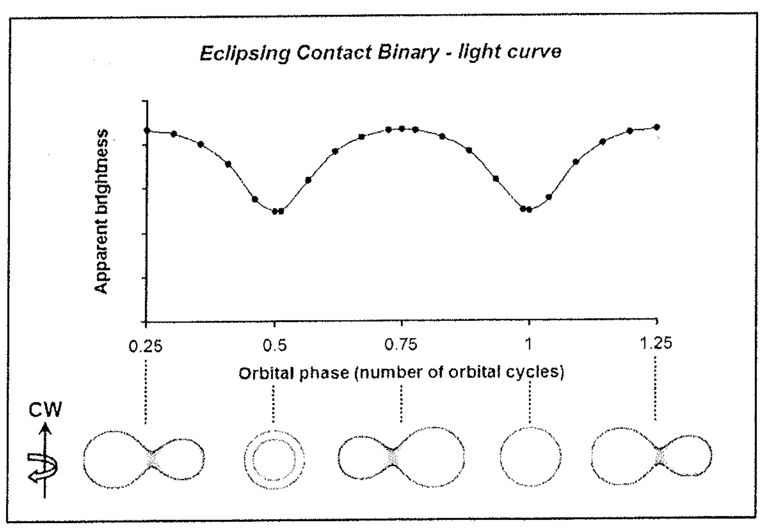

Figure 3: From http://cronodon.com/SpaceTech/BinaryStar.html

c) **Now make a similar set of diagrams for a system (again, observed from Earth) where the diameter of the primary is several orders of magnitude larger than the secondary and the two masses are separated by 100 primary radii, so now it is an eclipsing binary (same orbital geometry) rather than a contact binary. (5 points)**

Something like the below diagram is what I had in mind for this question.

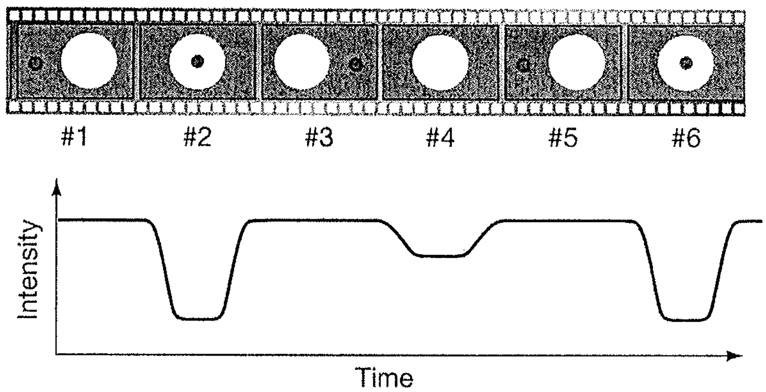

Figure 4: Cartoon of an eclipsing binary light curve.

d) **Describe qualitatively how the two light curves you drew should be different, and why. (3 points)**

The relative sizes as well as the shapes of the dips in the light curve should be different between the two scenarios. If the primary and secondary are similar sized, the dips should be correspondingly similar in size. There should be more flat line for the eclipsing binary, corresponding to times when you see the integrated flux from both components.

8. **One puzzle revealed during the *New Horizons* flyby of MU69 is that the light curve measured by the spacecraft had a very small amplitude. What could cause this, given that the shape of MU69 was determined to be bi-lobate from Earth-based occultation measurements made in the summer of 2017? (3 points)**

In order to answer this question you first needed to understand what is meant by a light curve having a "small amplitude." This means that the min/max brightness values are not that different from each other, *i.e.* there is not a dramatic dip in brightness throughout one complete rotation. Yet the light curve depicted in Fig. 3 above does show a substantial brightness variation.

Several explanations have been proposed for this puzzle (see `https://earthsky.org/space/new-horizons-approaching-ultima-thule-dec-2018` for more details). These include (1) perhaps the rotational pole of MU69 was pointed in the direction of the *New Horizons* spacecraft, (2) perhaps MU69 is surrounded by a cloud of dust that makes the observation and interpretation of its light curve more challenging, or (3) perhaps MU69 is surrounded by a number of tumbling moons, each of which would have its own light curve and the superposition of them would make it seem like MU69 has a small light curve.

You were not expected to know about these explanations *a priori*, so I was looking for you to make any kind of reasonable argument for an effect that would result in the detection of a small light curve.

9. **Provide a qualitative discussion of how the contact binary Ultima Thule could have formed. Given your answer, why do you think we don't we see many contact binaries in the solar system? (4 points)**

As depicted below, Ultima Thule may have formed when two fairly large remnants of the gas and dust leftover from the formation of the Sun and solar system gently collided and stuck together.

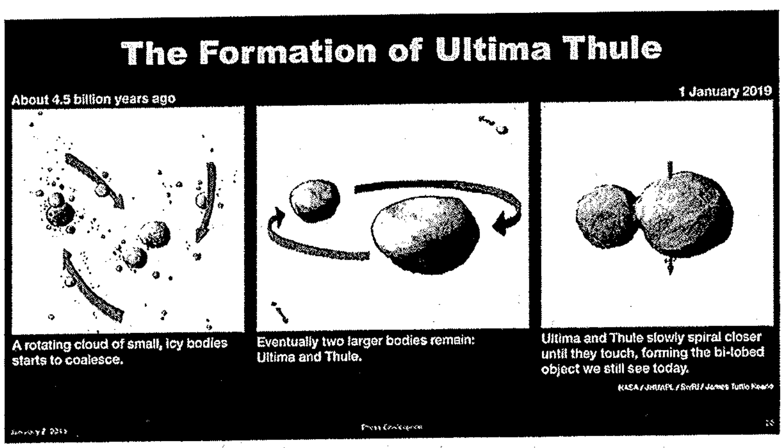

Figure 5: From https://www.space.com/42889-new-horizons-ultima-thule-flyby-planet-formation.html

It may be that we do not see more contact binaries in the solar system because these "pebbles" were swept up by larger protoplanetary bodies. Or, perhaps they were disrupted through gravitational encounters with other objects in the early solar system.

The MU69 Environment

10. **In the final paragraph the authors state that no dust impacts were detected inside MU69's Hill sphere.**

a) Describe in words what a Hill sphere is. (3 points)

A Hill sphere can be thought of as a "gravitational sphere of influence" of a secondary object that is in orbit around a primary. Usually in solar system applications the primary is the Sun and the secondary is something in orbit around the Sun (a planet or a Kuiper Belt Object, for example). The Hill sphere of MU69 defines the boundary where an object could be in orbit around MU69 rather than around the Sun.

b) Calculate the size of MU69's Hill sphere, stating whatever assumptions you made in order to do the calculation. (5 points)

The equation for the radius of a Hill sphere is

$$R_H = \left(\frac{m_2}{3(m_1 + m_2)} \right)^{\frac{1}{3}} a, \tag{5}$$

where in this case m_1 is the mass of the Sun, m_2 is the mass of MU69, and a is the distance between the Sun and MU69 (43 AU). Using the mass of MU69 that we calculated in Problem #3, we get R_H = 65,000 km.

c) In the final paragraph the authors also state that "no satellites were detected down to 1.5 km diameter (under the assumption of an Ultima Thule-like reflectivity) outside of 1000 km from Ultima Thule." How significant do you think this result is? (3 points)

Given how small MU69 is and how large its Hill sphere is (tens of thousands of km!), I did not find this result to be terribly useful or exciting. The final sentence of the paper is key ("A search for closer rings or satellites has not yet been performed."), and it means that the authors cannot yet definitively say that MU69 has no satellites larger than 1.5 km in size, just that there are no satellites far out. The presence or absence of satellites in general would be interesting in that it could provide some constraints on the formation and dynamical evolution of MU69.