Probing the Hill Sphere of (486958) 2014 MU\textsubscript{69}: HST FGS Observations during the 2017 July 17 Stellar Occultation

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Abstract

We observed the 2017 July 17 stellar occultation of HD 168233 by the Kuiper Belt Object (486958) 2014 MU\textsubscript{69}, the close flyby target of the extended New Horizons mission. Rather than capture a solid body occultation by the KBO itself, our program aimed to constrain the opacity of rings, moons, or other debris in the nearby environment. We used the Hubble Space Telescope Fine Guidance Sensors (HST FGS) instrument in TRANS F583W mode to collect 40 Hz time resolution photometry of the stellar occultation star for two HST orbits during this observation. We present the results of reduction and calibration of the HST FGS photometry, and set upper limits on rings or other dust opacity within the Hill sphere of (486958) 2014 MU\textsubscript{69} at distances ranging from $\sim$20000 km to $\sim$75000 km from the main body.

Key words: Kuiper belt objects: individual ((486958) 2014 MU\textsubscript{69}) – occultations – techniques: photometric

1. Introduction

The Kuiper Belt object (486958) 2014 MU\textsubscript{69} (hereafter MU\textsubscript{69}) was discovered in 2014 June using the Hubble Space Telescope. It is part of the cold classical Kuiper Belt, a structure that has been mostly undisturbed since the formation of the solar system. MU\textsubscript{69} has a semimajor axis of 44.4 au and orbits the Sun with a period of 295 years. Based on its apparent V-magnitude near 27, the diameter of the body is likely to be 20–40 km, depending on surface albedo. The recent results of M. W. Buie et al. (2018, in preparation) constrain its size further, as well as indicate it is likely a contact binary and may have at least one satellite. It is the current target of the NASA New Horizons spacecraft, which is on its way toward a planned 2019 January 1 flyby of this distant object (Stern et al. 2018).

Pre-encounter observations of potential rings or dust in the environment of MU\textsubscript{69} provide a critical role in avoiding spacecraft destruction given the 14.4 km s\textsuperscript{-1} New Horizons flyby speed. Rings or other dust opacity structures have previously been detected during stellar occultations around two Centaurs (KBO escapees): 10199 Chariklo (Braga-Ribas et al. 2014) and 2060 Chiron (Ruprecht 2013; Ortiz et al. 2015; Ruprecht et al. 2015). In the case of Chariklo, these rings are located about 400 km from the center of a body that is roughly 250 km in diameter; for Chiron, the rings (or possibly some other dust structure type) are about 320 km from the center of a body that is roughly 220 km in diameter. More recently, stellar occultation observations revealed that the dwarf planet Haumea also has a ring (Ortiz et al. 2017). This large trans-Neptunian object has a volume-equivalent diameter of $\sim$1595 ± 11 km, with the rings located approximately 2287 km from the center of the body.

MU\textsubscript{69} is much smaller than these bodies, but its lower gravity could still maintain at least a transient amount of dust or debris in the system. Analyses of the more similarly sized moons of Pluto, Nix (radius $\sim$44 km) and Hydra (radius $\sim$36 km), also showed that the low escape velocities of these objects can enable a significant amount of mass to escape given the micrometeorite bombardment rates expected in the Kuiper Belt (Stern et al. 2006; Stern 2009; Poppe & Horányi 2011). Additionally, stellar occultations of MU\textsubscript{69} itself suggest that the object is likely a binary or contact binary (M. W. Buie et al. 2018, in preparation). Binary and multiple systems are predicted to make up at least 20% of the cold, classical Kuiper Belt population (Stephens & Noll 2006). If MU\textsubscript{69} does have an additional, widely separated companion in its system, that object could serve as a potential source for an impact-induced, dusty ring far from the central body, perhaps in a similar way that the Phoebe ring extends radially to $\sim$18% of Saturn’s Hill sphere (Verbiscer et al. 2009).

For this reason, HST GO/DD program 15003 was designed to make a deep probe of the Hill sphere region of MU\textsubscript{69} during the 2017 July 17 stellar occultation. We discuss the background and planning of the observations in Section 2 and outline the HST FGS data reduction process in Section 3. We estimate upper limits on opacity and discuss these results in Sections 4 and 5, respectively.

2. HST FGS Observation Planning and Viewing Geometry

The Hubble Space Telescope Fine Guidance Sensors (HST FGS) are large field-of-view white light interferometers generally used for precision pointing of the telescope, but which also function as a science instrument capable of relative astrometry, detection of close binary systems, and 40 Hz relative photometry with milli-magnitude accuracy (Nelan 2017). This last feature makes it a powerful platform for observing stellar occultations by smaller bodies, which often occur over very short timescales ($\sim$-s). The HST FGS have previously been used to observe stellar occultations by solar system objects, as in the case of Triton (Elliot et al. 1998, 2000).

Unlike for relatively larger bodies like Triton, the stellar occultation by MU\textsubscript{69} cast a much smaller shadow, and
therefore the odds of \textit{HST} being able to observe the solid body passing in front of the star were exceedingly low. However, the event presented an opportunity to probe the nearby environment of MU69, in case significant opacity existed due to rings or some other debris source. We approximate the Hill sphere radius of MU69 as

\[ r = a (1 - e) \sqrt{\frac{m}{3 M_\odot}} \quad (1) \]

with a semimajor axis \( a \) of 44.4 au; an eccentricity \( e \) of 0.04; and the mass of the Sun, \( M_\odot \), of 1.989 \times 10^{30} \text{ kg}. We assumed a conservatively small diameter of 20 km and a mean density of 2 \text{ g cm}^{-3} to estimate that the mass, \( m \), of MU69 would be on the order of 10^{16} \text{ kg}. Therefore, the Hill sphere radius would be \( \sim 75000 \text{ km} \). This region casts a much larger shadow during the stellar occultation than the central body itself. For that reason, the observations acquired during this program were designed to cover two \textit{HST} orbits overlapping the mid-time of the stellar occultation as seen from Earth on 2017 July 17.

Due to the orbital geometry of \textit{HST}, it was inevitable that during part of the stellar occultation window, the Earth itself would occult the view of MU69 and preclude the measurement of useful data. Unfortunately, this occurred near the mid-point of the occultation when the projected distance between the star and MU69 was at a minimum, as shown in Figure 1. However, the observation by \textit{HST} still probed a region of the MU69 Hill sphere at radii down to \( \sim 20000 \text{ km} \). Uncertainty in the sky-projected position of MU69 based on the ephemeris used in this work was approximately 20 km at the time of the observation.

\textbf{3. Data Reduction}

The measurements acquired by \textit{HST} FGS are initially reported in raw data counts at 40 Hz time resolution for each of the 4 photomultiplier tubes (PMTs), as well as the encoded Star Selector A and B positions (SSENCA and SSENCB). Additionally, the data files contain flags updated every 150 msec that store the ongoing status of the instrument, including whether the target star has been detected and tracking has been engaged. For purposes of photometric analysis, we filtered the data using these flags to avoid instrument slews and only examined times when the instrument was tracking the target star in FineLock mode (Nelan & Makidon 2002). We then summed the counts from all four PMTs into the total measured counts shown in Figure 2. The data from the first orbit consists of two segments: a wider \( \sim 5 \text{ minute} \) scan in order to rule out the presence of a binary companion near the target star, and a more focused \( \sim 30 \text{ minute} \) scan to monitor stellar photometry. This scan mode was then continued in the second \textit{HST} orbit for another \( \sim 35 \text{ minutes} \) of data.

The measured FGS count rate is sensitive to the instantaneous pointing of the instrument, and this effect will dominate over relatively small signals of opacity along the line of sight. However, the encoded Star Selector A and B positions allow for an empirical fit to determine the relationship between these pointing positions and the total measured count rate. This is shown in Figure 3, where the measurement of total counts is seen to be a consistent function of the encoded SSENCA and SSENCB values.

We constructed a simple forward model prediction of total counts based on the known values of SSENCA and SSENCB during each segment of the \textit{HST} observation. At each time step, the expected variation in observed counts due solely to instrument effects, \( C_{\text{inst}}(t) \), is derived from a weighted mean of the counts measured at all other times when the sensor was in the same scan position, as described in Equations (2) and (3).

\[ w_i(t) = \begin{cases} \quad \text{if } SSENCA(t) = SSENCA(t_i) \\ \text{SSENCB}(t) = SSENCB(t_i), \text{ otherwise} \end{cases} \quad (2) \]
This model allows for the removal of the periodic effects from the instrument scan itself before we search for transient, time-correlated signal from possible opacity along the line of sight to the star. The modeled counts ($C_{\text{inst}}$) are shown in Figure 4, along with the residuals ($C_{\text{obs}} - C_{\text{inst}}$) and normalized light curve ($C_{\text{obs}} / C_{\text{inst}}$) derived from comparison with the observed counts. Poisson noise from the stellar source sets the signal-to-noise ratio ($S/N$), which can be estimated as $\sqrt{N}$ where $N$ is the number of observed counts during a given time interval. Therefore, we find that $S/N \sim 20$ at the observed 40 Hz time resolution (or $S/N \sim 126$ given a 1 s time interval).

4. Upper Limits on Rings and Dust Opacity

4.1. Numerical Modeling Method

While no signatures of opacity were immediately apparent in the photometry, we further adapted the forward model to determine upper limits on potential absorption by rings or dust in the nearby environment of MU69. We added a simple three-parameter ring model for comparison: with $t_c$, the time at center
of opacity during the observation; $\Delta t$, the duration of the occultation by a ring or other opacity feature; and $\tau$, the line-of-sight optical depth. We modeled the ring opacity as a boxcar function and tested durations of $\Delta t$ ranging from 0.25 to 3.5 s (approximately equivalent to ring widths of 5–70 km).

Ortiz et al. (2017) and Bérard et al. (2017) modeled the rings around Haumea and Chariklo, respectively, with the assumption that they are coplanar with the equator of the main body. The rings also have some angle $B$, known as the ring-opening angle, or the angle between the ring plane and the line-of-sight vector of the observer. The pole orientation of MU69 is currently unknown due to the limited data available, so for simplicity and due to the lack of constraints from existing observations, we do not consider $B$ as a free parameter in this work. Instead, we assume a pole-on geometry ($B = 90^\circ$) for the rings. As a result, the line-of-sight optical depths reported in this work serve as upper limits to the normal optical depth $\tau_0$, defined as $\tau_0 = \tau \sin B$. The normal optical depth is the optical depth that would be observed if the line of sight were perpendicular to the ring plane.

Based on this three-parameter model, as a function of time, the line-of-sight transmission is described as

$$T(t, t_c, \Delta t, \tau) = \begin{cases} 1 & \text{if } t < t_c - \frac{\Delta t}{2} \\ e^{-\frac{t - t_c}{\Delta t}} & \text{if } t_c - \frac{\Delta t}{2} \leq t \leq t_c + \frac{\Delta t}{2} \\ 0 & \text{if } t > t_c + \frac{\Delta t}{2} \end{cases},$$

which leads to the modified version of Equation (3):

$$C_{\text{model}}(t, t_c, \Delta t, \tau) = T(t, t_c, \Delta t, \tau) \times \frac{\sum_{i=1}^{n} W_i(t) C_{\text{obs}}(t_i)/T(t, t_c, \Delta t, \tau)}{\sum_{i=1}^{n} W_i(t)}.$$

This step requires an additional factor of $T(t, t_c, \Delta t, \tau)$ within the summation in order to account for the secondary effect of opacity on the instrument correction itself. Without this factor, the effect of any dips in $C_{\text{obs}}$ due to opacity along the line of sight would bias the calculation of $C_{\text{inst}}$ and by extension $C_{\text{model}}$. Thus, the potential biasing effect of attenuation can be effectively negated by dividing $C_{\text{obs}}$ by the model transmission as shown here.

We demonstrate a few examples of potential ring opacity by using a synthetic light curve. The synthetic data, $C_{\text{syn}}$, was calculated as

$$C_{\text{syn}}(t) = C_{\text{inst}}(t) + \mathcal{N}(0, \sigma^2)$$

where $\mathcal{N}(0, \sigma^2)$ represents a random draw from a normal distribution, centered on zero, with the same standard deviation as the observed data. Adding opacity is done in a straightforward manner as

$$C_{\text{syn, model}}(t, t_c, \Delta t, \tau) = T(t, t_c, \Delta t, \tau) C_{\text{syn}}(t).$$

We generated several cases of synthetic ring absorption (models a–i), which represent the various combinations of ring model parameters shown in Figure 5. We also compare these model parameter values to previously detected ring systems in Table 1.

In order to determine upper limits on opacity, we analyzed the parameterized model $C_{\text{model}}(t, t_c, \Delta t, \tau)$ and the observed $C_{\text{obs}}(t)$ within a Bayesian statistical framework. For computational efficiency, we calculated the posterior log likelihood of the model with a few selected values of $\Delta t$ over all reasonable values of $t_c$ and $\tau$. The log likelihoods of the null case (no opacity) and the model with a given set of ring parameters were derived from the following set of equations:

$$y(t) = C_{\text{obs}}(t)$$

$$\sigma(t) = \sqrt{y(t)}.$$

If $\tau = 0$, as in the null case, then the following is true:

$$C_{\text{model}}(\tau = 0) = C_{\text{inst}}(t)$$

$$\log L(\tau = 0) = -\frac{1}{2} \sum_{i=1}^{n} \frac{(C_{\text{obs}}(t_i) - C_{\text{inst}}(t_i))^2}{\sigma(t_i)^2},$$

**Figure 4.** Observed HST FGS counts during the occultation window, and the normalized light curve after correction for instrumental effects. Top panel: $C_{\text{obs}}$, the total counts measured by HST FGS. Second panel: $C_{\text{inst}}$, the modeled counts based on instrument effects for each segment of the observation. Third panel: $C_{\text{obs}} - C_{\text{inst}}$, the residual of model subtracted from observation. Bottom panel: $C_{\text{obs}}/C_{\text{inst}}$, the normalized light curve after correction.
We verified the upper limits on the ring optical depth derived in the previous section using an analytic approach. We looked for statistically significant outliers in the data set at various spatial resolutions, following a similar technique used by Throop et al. (2015) to search for rings around Pluto during the New Horizons flyby.

We applied this approach only to the final two focused scans, excluding the initial data that was collected to rule out the presence of a binary companion. For these \( N = 153,330 \) data points, we would expect that about 400 data points (or 0.26\%) would fall above or below the 3\( \sigma \) range and find 428 such points in the data. In Figure 7, we bin the data to spatial resolutions comparable to the rings discovered around other small bodies and also explore the case of an extremely extended (1000 km wide) ring. For the case of the 1000 km, 70 km, 10 km, and 5 km binned data sets, we would expect to see 0.2, 4.5, 29.3, and 53.6 data points fall outside of the 3\( \sigma \) level, respectively. We find 0, 4, 37, and 48 points for each of those cases, further indicating that there are not likely any statistically significant outliers that would be suggestive of a ring or debris.

We use this additional information to place upper limits on the optical depth of a putative ring around MU69. The equation for optical depth is defined as \( I = I_0 e^{-\tau} \), where \( I \) and \( I_0 \) are the occulted and unocculted stellar signal, respectively. We used this relation to solve for the optical depth of a ring that would cause a 3\( \sigma \) detection in each data set. These results are listed in Table 2 and are consistent with the upper limits on optical depth derived from the numerical model analysis discussed in the previous section.

### 5. Discussion

The HST FGS observation of the 2017 July 17 stellar occultation was successful and provided upper limits on sources of opacity within the Hill sphere of MU69. While
HST was unable to observe the target star during the mid-point of the occultation, the results still probed down to radii of about 20000 km from the main body. At these distances, the data rule out significantly opaque sources at effective ring widths of \( \sim 5 \) km or more.

These results provide additional context for the summer 2017 campaign of MU69 stellar occultation measurements made by ground- and air-based observatories as reported in M. W. Buie et al. (2018, in preparation) and elsewhere. These collective upper limits on sources of opacity in the MU69 system will be invaluable as planning continues for the 2019 January 1 flyby of MU69 by New Horizons.

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**Figure 6.** \(3\sigma\) (99.7% cumulative probability) upper limits on \(\tau\) during the observation given a model value of \(\Delta t\) (or \(w\), the equivalent ring width). The model ring widths shown were chosen to roughly correspond to the observed ring parameters of Haumea and Chariklo (see Table 1).

**Figure 7.** Normalized light curves binned to different spatial resolutions. No statistically significant signatures of opacity were found in any of the binned data sets.

| Bin Width | No Binning | 5 km | 10 km | 70 km | 1000 km |
|-----------|------------|------|-------|-------|--------|
| \(\tau\) (3\(\sigma\) limit) | 0.146 | 0.057 | 0.042 | 0.017 | 0.005 |

**Table 2**

Upper Limits on \(\tau\): Analytic Results
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