High-precision Orbit Fitting and Uncertainty Analysis of (486958) 2014 MU69

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Abstract

NASA’s New Horizons spacecraft will conduct a close flyby of the cold-classical Kuiper Belt Object (KBO) designated (486958) 2014 MU69 on 2019 January 1. At a heliocentric distance of 44 au, “MU69” will be the most distant object ever visited by a spacecraft. To enable this flyby, we have developed an extremely high-precision orbit fitting and uncertainty processing pipeline, making maximal use of the Hubble Space Telescope’s Wide Field Camera 3 (WFC3) and pre-release versions of the ESA Gaia Data Release 2 (DR2) catalog. This pipeline also enabled successful predictions of a stellar occultation by MU69 in 2017 July. We describe how we process the WFC3 images to match the Gaia DR2 catalog, extract positional uncertainties for this extremely faint target (typically 140 photons per WFC3 exposure), and translate those uncertainties into probability distribution functions for MU69 at any given time. We also describe how we use these uncertainties to guide New Horizons, plan stellar occultations of MU69, and derive MU69’s orbital evolution and long-term stability.

Key words: astrometry – celestial mechanics – Kuiper Belt: general – Kuiper Belt objects: individual (2014 MU69) – occultations

Supporting material: machine-readable table

1. Introduction

The cold-classical Kuiper Belt Object (KBO) (486958) 2014 MU69 is the primary target for NASA’s New Horizons Kuiper Belt Extended Mission. The cold-classical Kuiper Belt consists of objects on low-eccentricity, low-inclination (<5° to the invariant plane) orbits (that is, dynamically “cold”) with heliocentric semimajor axes between about 40 and 50 au. The cold-classical objects were likely formed in-place and escaped perturbation from their initial orbits by giant planet migration (Batygin et al. 2011, and references therein), making them the most distant known remnants of the original protoplanetary disk.

NASA’s New Horizons spacecraft was launched 2006 January 19, received a gravitational assist from Jupiter on 2007 February 28, and flew through the Pluto-Charon system on 2015 July 14 (Stern et al. 2015). Since the Pluto encounter, New Horizons has observed the 3:2 Neptune resonant (15810) Arawn ( provisionally designated 1994 JR1) in 2016 as close at a distance of 0.7 au (Porter et al. 2016). New Horizons will encounter many other KBOs within 1 au, some as close as 0.1 au, and some (such as Quaoar and Haumea) that are much farther away, but all can be seen by New Horizons at much higher solar phase angles than is possible from Earth-based telescopes (S. B. Porter et al. 2018, in preparation, A. J. Verbiscer et al. 2018, in preparation). However, none of these KBOs will be seen as close as MU69, which will be within 3500 km of the spacecraft on the nominal trajectory. New Horizons will image the surface of MU69 at best resolutions of ≈35 m/pixel, and spectral maps at ≈1 km/pixel. In order to guide the spacecraft to such a close encounter with a KBO that only has a relatively short orbital arc are required a completely new approach to orbit determination and uncertainty analysis, which we describe in this paper.

2014 MU69 was discovered in 2014 July by the Hubble Space Telescope (HST) following eight years of dedicated searches for a second New Horizons encounter object (M. W. Buie et al. 2018, in preparation). After several ground-based searches down to V ≈ 26, 194 HST orbits were allocated for a deeper, more systematic search for objects accessible to New Horizons (GO 13633, PI Spencer). MU69 was initially detected in 10 images acquired in two HST orbits, as were four other KBOs during the HST search. Three objects were potential targets for New Horizons: 2014 MU69, 2014 OS303, and 2014 PN79. In 2015 August, the New Horizons team selected 2014 MU69 as the potential New Horizons extended mission target. The spacecraft performed a series of four burns in 2015 October–November to target 2014 MU69. The New Horizons Kuiper Belt Extended Mission was approved by NASA after Senior Review in 2016 July, and its centerpiece is the flyby of 2014 MU69 on 2019 January 1.

In this paper, we will discuss our process of performing absolute astrometry on 2014 MU69 tied to a pre-release version of Gaia DR2, propagating that error forward to orbital uncertainty, and then using the orbital uncertainty to guide both occultations of the KBO and to guide the spacecraft to a close flyby. These techniques represent the highest-precision heliocentric orbit fitting of a KBO ever, and they can provide a basis for future applications of Gaia-driven astrometry to small bodies in the solar system.

2. Data Sources

2014 MU69 was discovered with the HST search program (GO 13633) described in (M. W. Buie et al. 2018, in
This program was designed to take five full-frame 370 s Wide Field Camera 3 (WFC3) UVIS images in one orbit with the F350LP broadband filter, skip an HST orbit, and then repeat the same observation. The images were tracked on a nominal cold-classical orbit, producing streaked stars, but nonstreaked KBOs. To perform the search, the images were shift-stacked at 20 different representative cold-classical shift rates. Objects that appeared in both search orbits for one of the shift rates were identified and targeted for follow up HST observations. The first object identified this way was designated 1110113Y (HST orbit IDs 11/12, WFC3 CCD 1, shift rate ID 011, random ID 3Y), later given the provisional designation 2014 MU69. Four more KBOs were subsequently detected, all of which were brighter, but all of which required more fuel for New Horizons to reach.

The available data set for 2014 MU69 has both a short temporal arc (2014 July–2017 October) and an extremely high data quality, making it ideal for the analysis described below. MU69 is a very faint object, with $V \approx 27.5$ (S. Benecchi et al. 2018, in preparation) and is in an extremely crowded star field (galactic longitudes from $-8^\circ$ to $-12^\circ$). These constraints have made it effectively impossible to detect with ground-based telescopes, and all observations of MU69 have been with the Hubble Space Telescope. A list of these HST observations is in Table 3.

Both the initial follow up observations and most observations conducted since then have adopted the search program’s basic format of five 367 to 370 s, F350LP filter, full-frame UVIS WFC3 images. The key exceptions are the color campaign in summer of 2016 (GO 14092, PI Benecchi), in which four orbits each included two 348 s images using F606W followed by three 373 s images with F814W. As shown in Table 3, half of the follow up orbits were roughly evenly spread over 2014 August–2017 October, while the other half were spread over a roughly one week interval in 2017 June–July. The latter was the light-curve campaign (GO 14627, PI Benecchi), which was critical in successfully predicting the 2017 July occultation (see Section 6).

In addition to HST and the 2017 July occultation, the other data source for this analysis was stellar astrometry from the ESA Gaia project. Initially, the process in Section 3 was built using a custom star catalog built from a deep composite of the MU69 field obtained using the Canada–France–Hawaii Telescope (Gwyn 2014). When the Gaia Data Release 1 (DR1) was made available in 2016 September (Gaia Collaboration et al. 2016), we began using that, applying a mean proper motion correction to images significantly after the DR1 2015.0 epoch. The mean proper motion was calculated from the Gaia TGAS catalog (Michalik et al. 2015). The MU69 observation fields were in areas of very low coverage for TGAS, so the TGAS stars could not be used directly. With the success of our application of DR1 and after a special support request to the Gaia project, we were able to obtain a sky patch from a pre-release version of Data Release 2 (DR2) around the path of MU69. The major advances with DR2 are proper motion for all catalog stars, obviating the need for a mean proper motion correction, as well as a much more homogeneous, bias-free distribution of errors on the sky, and much lower uncertainty (one order of magnitude). This early version of DR2 was used to plan the three 2017 occultations, both for correcting the HST absolute astrometry and for knowledge of the occultation stars themselves. We obtained a second preview version of DR2 in our field of interest in 2017 October, and that version is used for the astrometry in Table 3.
the original WCS. This process was repeated 10,000 times to build a discretely sampled PDF of the WCS offsets. The resulting typical 1σ uncertainty in the CRVAL1 and CRVAL2 keywords (and thus in the pointing of HST) was <2 mas.

The pixel position PDFs for the KBO used the same basic MCMC algorithm as the star pixel PDFs, but with the single walker iterated 10000 times to build the PDF. Because HST tracked on the KBO, we did not need a smear kernel to fit the KBO and could use a Tiny Tim PSF directly. In addition, all but the discovery observations had MU69 near the center of WFC3 chip 2 (FITS extension 1), making for a less distorted PSF than near the chip edges. Initially, the KBO fit was started with a manual click on the rough position of the KBO in the image. However, as the orbit improved, this manual position was replaced with a calculated initial position from prior orbit solutions and the WCS. We also made manual masks of stars and cosmic rays near the KBO that might adversely affect the PDF generation.

Finally, we needed to combine the KBO pixel PDFs with the WCS PDFs to make KBO sky PDFs. Similarly to the WCS PDFs, this was accomplished by selecting a randomly selected KBO pixel location with a randomly selected WCS PDF, translating to R.A. and decl., and then repeating 10000 times. An example of one of these PDFs is shown in Figure 2. The instrument magnitude in the pixel PDF was converted to AB apparent magnitude with the PHOTFLAM header keyword. While the magnitude was not used directly for astrometry, it was an important diagnostic for the quality of the pixel PDF. For the solutions presented, we filtered out any points with magnitude uncertainties larger than 0.5, which were generally failures to fit the object, or any points with uncertainties smaller than 0.1 mag, typically a cosmic ray close to the KBO causing spuriously high signal-to-noise ratios. We also only used the F350LP points for the orbit, as the narrower-band points had worse signal-to-noise ratios for both stars and MU69. This left 214 of the 264 images, which we used for an initial fit. An additional nine points were rejected because they had greater than 30 mas residuals relative to the initial fit. Our final HST astrometry thus used 205 of the 264 images (78%); these are shown in Table 3.

After the method described here was used to successfully predict the occultation of MU69 on 2017 July 17 (See Section 6, M. W. Buie et al. 2018, in preparation), we were able to use the occultation itself as a high-quality occultation point. Because five solid-body chords were obtained on July 17, we chose the mid-time of the longest chord and used it as the nominal center-of-figure. We could then combine this mid-time, the topocentric location of the portable telescope that obtained the longest chord, and the location and uncertainty of the occultation star from Gaia DR2 to produce an effective astrometric PDF. See M. W. Buie et al. (2018, in preparation) for more details about the circumstances and analysis of this occultation. This occultation PDF could then be combined with the HST-derived PDFs in the process described in Section 4.

4. Orbit Determination

Typically, small body orbits in the literature are described in either mean or osculating heliocentric elements, with error bars representing a normal error distribution. This is typically sufficient
for general dynamical studies and rough targeting from the ground, but not for spacecraft flybys or occultation planning. The actual uncertainty of an object’s astrometry is rarely perfectly described by a normal distribution, and neither is that object’s location and velocity in space. We thus sought to develop an orbit-fitting method that would accurately map the full astrometric uncertainty distribution into the ephemeris.

To perform these fits, we developed a high-precision few-body orbital integrator. As 2014 MU₆₉ is a cold-classical KBO, all of the planetary perturbations on it are interior, and tend to result in a slow precession. Non-gravitational forces (i.e., YORP) and general relativity are not a factor for KBOs. We therefore developed a few-body conservative force integrator, capable of modeling the major planets and their perturbing forces on a massless test particle. This integrator (PyNBody⁵) is based on the 12/13 order Runge–Kutta-Nystrom integrator of Brankin et al. (1989) and was previously described in Porter et al. (2016). This integrator is not the fastest, but it is very accurate and can typically conserve system energy and momentum to within machine precision over the relevant timescales for orbit fitting.

The KBO’s orbit is parameterized as a Cartesian state vector relative to the solar system barycenter at a fixed epoch. The inertial frame for the integrations the International Celestial Reference Frame (ICRF). Gaia DR1 is aligned to ICRF by matching optical detections of quasars with a subset of ICRF2, while Gaia DR2 uses several thousand quasars from ICRF3 and half a million AGNs to perform frame alignment (Gaia Collaboration et al. 2016). The integration epoch is set to 2014-06-01 00:00:00 UTC, a few weeks before the first observation (originally a safety factor in case of any precoveries in the HST search). To test the solution against the data, we propagate the state vector with the PyNBody integrator to the desired time and calculate its apparent ICRF R.A./decl. from HST, with appropriate light-time correction. We use the JPL NAIF HST and DE430 SPICE kernels to determine the location of HST relative to the solar system barycenter (Folkner et al. 2014).

We used the emcee Markov-Chain Monte Carlo package (Foreman-Mackey et al. 2013) to translate the astrometric uncertainty to orbital uncertainty. The emcee package provides a fast and natively multithreaded way to run MCMC from Python. As input to emcee, the fitting program calculates the likelihood for any solution by taking the predicted R.A./decl. for that solution and comparing them to the R.A./decl. PDFs. Because the PDFs are discretely sampled, we created a Kernel Density Estimator for each observations, using Silverman’s Rule of Thumb (Silverman 1986) to choose the bandwidths, as most of the PDFs were roughly Gaussian. The log likelihoods for all the images could then be summed to provide a total log likelihood to emcee.

For any solution, the first step is to make an initial guess (typically an older solution) and minimize its χ² with a downhill simplex method (Nelder & Mead 1965). This polished solution is then used to create 200 slightly perturbed state vectors as the initial “walkers” for emcee to use. We then run the 200 walkers for 100 iterations to “burn-in” and allow them to move away from the artificial initial distribution. We then reset emcee and run it for 500 iterations to produce the full PDF cloud of 10,000 state vectors at the fitting epoch. These numbers of iterations were arrived at after much testing and are typically more burn-in than is actually necessary, so as to ensure that the solutions are well-distributed. We save the resulting state vector PDF in a format that can then be propagated to any time of interest. The state vector and orbit for our “rd2b” orbit solution are presented in Table 1.

| Value | 1σ |
|-------|----|
| x     | ± 1.16313074444e+09 | ± 2.80223e+02 km |
| y     | ± 6.385039581373e+09 | ± 1.52754e+03 km |
| z     | ± 2.373261916929e+08 | ± 5.87015e+01 km |
| vₓ    | ± 4.61378977477e+00 | ± 5.92714e-06 km s⁻¹ |
| vᵧ    | ± 9.61922770583e-01 | ± 2.45488e-05 km s⁻¹ |
| vₑ    | ± 1.066958207821e-01 | ± 9.45150e-07 km s⁻¹ |

Note. State vector and orbit are relative to the solar system barycenter and in the ICRF ecliptic frame at the epoch 2014-06-01 00:00:00 UTC.

We thus proposed and were awarded six observations would be required to enable a close analysis described here showed that significantly more HST observations would be required to enable a close flyby of 2014 MU₆₉. We thus proposed and were awarded six HST orbits in 2016, and five in 2017 (GO/DD 14485, GO 14629, and GO 15158, PI Buie). In addition, 24 HST orbits were used in 2017 June/July to measure the light curve of MU₆₉ (GO 14627, PI Benecchi). The orbit presented here uses data from all of these HST programs, in addition to the July 17 occultation.

The New Horizons spacecraft will nominally fly closest to 2014 MU₆₉ at 05:33 2019 January 1 UTC. This time was chosen to enable both the Goldstone and Canberra Deep Space Network (DSN) 70 m dishes to uplink to the spacecraft simultaneously for an attempted bistatic radar experiment (as was performed at Pluto; Linscott et al. 2016). New Horizons will not be able to acquire MU₆₉ any earlier than 2018 August. Because of New Horizons’s almost radial trajectory out of the solar system, the KBO will move very slowly against the background stars until a just few weeks before encounter.

⁵ https://github.com/ascendingnode/PyNBody

5. New Horizons Trajectory Planning

The primary reason to determine the orbit of 2014 MU₆₉ to very high precision is to ensure the success of the New Horizons flyby. New Horizons performed the major Trajectory Correction Maneuver to guide it to MU₆₉ over a series of four burn segments in 2015 October and November, after all Pluto observations had finished. The initial orbit used to target the spacecraft was based on the first year of data, from 2014 June to 2015 July (GO 13633 and GO/DD 14053, PI Spencer). After that burn, early versions of the analysis described here showed that significantly more HST observations would be required to enable a close flyby of 2014 MU₆₉. We thus proposed and were awarded six HST orbits in 2016, and five in 2017 (GO/DD 14485, GO 14629, and GO 15158, PI Buie). In addition, 24 HST orbits were used in 2017 June/July to measure the light curve of MU₆₉ (GO 14627, PI Benecchi). The orbit presented here uses data from all of these HST programs, in addition to the July 17 occultation.

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While the spacecraft can use the LOng Range Reconnaissance Imager (LORRI; Conard et al. 2005) to well constrain the location of 2014 MU₉₀ in the “B-Plane” (the plane perpendicular to the spacecraft’s motion and containing the flyby target), the time-of-flight (ToF) uncertainty along the direction of the spacecraft’s motion is constrained only by the Earth-based orbital solution. The distance to the spacecraft from Earth will be well-constrained by Doppler radio measurements on approach to MU₉₀, and so the uncertainty in the absolute location of MU₉₀ relative to the solar system barycenter will determine the flyby ToF uncertainty.

6. Application to Occultation Planning

In addition to guiding New Horizons, we also used our orbit solution to predict three stellar occultations by 2014 MU₉₀ in 2017 and one in 2018. The 2017 occultation campaign is comprehensively described in M. W. Buie et al. (2018, in preparation) and here we detail only the procedures used to predict the occultations. MU₉₀ is a small object, with an absolute magnitude of Hₛ ≈ 11. S. Benecchi et al. (2018, in preparation), corresponding to a size likely smaller than 50 km diameter. We therefore knew that the occultations would only be successful if we had very high-quality orbital estimates and uncertainty models. Thankfully, that is exactly what we had developed for guiding New Horizons.

Stellar occultations occur when a solar system object passes in front of a star from the perspective of an observer. They have been used to discover the atmosphere of Pluto (Elliot et al. 1989) and the rings around Uranus, Chariklo, and Haumea (Elliot et al. 1977; Braga-Ribas et al. 2014; Ortiz et al. 2017, respectively). The latter is most important for planning the New Horizons flyby of MU₉₀, as occultations provide the only way of detecting rings or other opacity structures around the KBO before the spacecraft is close enough to see them directly. In addition, occultations can (and in this case did) provide estimates of the size and shape of a body. Knowledge of the approximate size of MU₉₀ enabled estimates of its bulk albedo, and therefore allowed mission planners to better estimate the correct exposure times for the flyby images.

Because of the motion and rotation of the Earth, stellar occultations sweep across Earth from west to east. The typical approach to observe an occultation of an object with an uncertain orbit is therefore to set up a north–south “picket fence” of portable telescope teams perpendicular or “crosstrack” to the occultation path. It is therefore important to know both the crosstrack uncertainty of the prediction, and what the crosstrack distance of any station is. The latter often requires some iteration, as finding a logistically viable site with the proper crosstrack can be challenging, especially in an unfamiliar country. We thus developed tools to export KML files to Google Maps with lines showing the target crosstracks for each observing team. These could be used for planning site reconnaissance, and with GPS-enabled smartphones, used to see in real time where a potential site was located compared to the desired crosstrack line. To estimate the crosstrack uncertainty, we propagated the full 10000 states to the occultation time and calculated the geometry for all of those states. This produced a full PDF of the occultation uncertainty, which we could use to plan the crosstracks to maximize the chance of success.

The first MU₉₀ occultation of 2017 was on June 3. The ground track for this event passed over both South America and South Africa, and 25 portable telescope teams were deployed to both Mendoza, Argentina and the Northern Cape and Western Cape Provinces of South Africa. Two HST astrometric observations of MU₉₀ had been planned for the spring of 2017, on March 16 and in mid May. However, the March observation failed due to a safing event on HST, and the observation could not be rescheduled in April, because MU₉₀ was passing through quadrature and did not have enough sky motion from HST to be detected. Thus, the first MU₉₀ observations of 2017 were acquired by HST on May 1 and 25. An initial solution though May 1, “may1c,” was used to plan the deployments to Argentina and South Africa. This was superseded by the “may25a” solution with data through May 25, which was produced after the orbit fitters (Porter and Buie) had deployed, and was used to plan the actual ground tracks. The “may25a” solution purported to have a crosstrack uncertainty of 44 km, though the subsequent 2017 June–July observations showed that the “may25a” ground track had been too far north by almost 2-sigma. This offset precluded a solid-body occultation on June 3, though the high signal-to-noise ratio observations of the event at the South African Astronomical Observatory 74 inch telescope and at Gemini South did exclude optically thick rings around MU₉₀. See M. W. Buie et al. (2018, in preparation) for more details.

The second MU₉₀ occultation of 2017 was on July 10. This event occurred mainly over the Pacific Ocean with a much dimmer star (V ≈ 15.5) and nearly full Moon, thus preventing a ground-based observation campaign. However, the NASA-DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) airborne observatory was able to reach the occultation track from its southern deployment base in Christchurch, New Zealand, and NASA awarded a flight to observe the July 10 occultation (PI E. Young). Between the June 3 and July 10 events, HST observed 2014 MU₉₀ over 24 orbits between June 25 and July 4 (GO 14627, PI Benecchi). This program provided a wealth of new images to integrate into the MU₉₀ orbit solution in a very short amount of time, and time was especially critical, as the last six orbits worth of data was downlinked from HST after the orbit fitting team (Porter and Buie) had arrived in Christchurch. Thus, the orbit solution used to guide the SOFIA flight was necessarily determined at the United States Antarctic Program Christchurch facility, and delivered to the SOFIA mission planners 36 hours before the flight. This orbit solution, “lc1,” used all of the light-curve campaign points, plus the highest-quality preceding HST MU₉₀ observations.

The final MU₉₀ occultation of 2017 on July 17 was observed with portable ground stations in the Chubut and Santa Cruz provinces in Argentina. No additional observations of HST MU₉₀ were made between the July 10 and July 17 occultations, but we did perform a more thorough filtering of low-quality points. This resulted in the “lc1gr” solution that was used to guide the placement of stations for the July 17 occultation. The “lc1gr” solution had a 1σ uncertainty in crosstrack of 13 km, much tighter than for June 3. This solution allowed a tighter picket fence of stations up and down the Patagonian coast, centered a few kilometers north of the city of Comodoro Rivadavia. Despite heavy winds on the occultation night, 22 of the 24 deployed stations successfully observed the occultation. Five of those stations observed the solid-body occultation, with the southernmost being the predicted centerline from the “lc1gr” solution.

This work predicts an additional stellar occultation opportunity on 2018 August 4. The ground track for this event passes over western Africa (Mali, Mauritania, and Senegal) and northern South America (Guyana, Venezuela, and Colombia). With the “rd2b” solution presented in Table 1, the 1σ crosstrack uncertainty is 12 km. This uncertainty will decrease somewhat with additional HST observations in 2018.
7. Long-term Orbital Evolution

2014 MU₆₉ is a cold-classical KBO. Elliot et al. (2005) identified the “Classical” KBOs as nonresonant objects with eccentricities smaller than 0.2. This classification was further refined as a “Cold Classical” or “Kernel” population by Petit et al. (2011) with $a \approx 44$ au, $e \approx 0.05$, $i < 5^\circ$ to the invariant plane. MU₆₉ has $a = 44.2$ au, $e = 0.03$, $i = 2^\circ$, making it an archetype of the cold-classical population. Batygin et al. (2011) showed the orbits of cold-classical objects were likely formed in-place and survived being disturbed from their initial orbits by giant planet migration. The unusually high binary fraction of cold-classical KBOs (Noll et al. 2008) is an additional line of evidence that they are mostly undisturbed from their original orbits. Indeed, the observed cold-classical KBO binary fraction is high enough that nearly all must have originally formed as binaries or higher-order multiple systems (Fraser et al. 2017).

With a few small modifications to the PyNBody code, we were able to integrate the orbit of MU₆₉ over sufficiently long timescales to test this stability and determine mean orbital elements. Specifically, we changed the unit in the integration from seconds to years to allow for longer integrations without worry of overflows and removed the terrestrial planets as perturbers (instead dropping their masses into the Sun). The results of integrations forward and back $10^8$ years can be seen in Figure 3 and Table 2, projected in both the mean solar system plane defined by the de430.bsp planets in the ICRF J2000 Ecliptic frame, $i_m = 1^\circ 6$ and $\Omega_m = 72^\circ 4$, and in the mean Kuiper Belt plane at 44 au as determined from known KBOs Volk & Malhotra (2017), $i_m = 1^\circ 8$ and $\Omega_m = 77^\circ$. The mean, free, and forced elements of MU₆₉’s orbit are shown in Table 2. The forced inclination of MU₆₉ to the mean solar system plane is 0°26, but only 0°0012 to the mean Kuiper Belt at 44 au. Likewise, the forced eccentricity of MU₆₉ is less than 0.0001. The apparent lack of any forced inclination or eccentricity to the mean Kuiper Belt is strong evidence that MU₆₉ has not suffered any significant orbital evolution beyond secular perturbations. MU₆₉ should therefore represent a truly pristine fossil of the Sun’s protoplanetary disk, an object unlike any other previously visited by a spacecraft.

8. Summary

We have described the process we have used to fit the orbit of 2014 MU₆₉, as of the start of 2018. This process combines Gaia DR2 and HST/WFC3 to produce extremely high-precision absolute astrometry of MU₆₉, and translates that uncertainty into a Cartesian state vector probability distribution function that can be evolved to any time of interest. The results of this analysis were used to successfully predict and observe a solid-body stellar occultation of MU₆₉ on 2017 July 17, predict a stellar occultation on 2018 August 4, and to guide the New Horizons spacecraft to a close (3500 km) flyby of MU₆₉ on 2019 January 1.

The process described here should enable high-precision orbit determination for future occultations and spacecraft missions. 2014 MU₆₉ presents the extreme case of a very interesting object that is both faint and in a very crowded star field. Now that the Gaia DR2 catalog has been released, solar system objects with higher signal-to-noise ratios should benefit even more from this technique, enabling a substantial improvement in orbital uncertainty and increasing the number of objects that might be observed with stellar occultations.

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Facilities: HST(WFC3), Gaia, SOFIA.

Software: astropy (The Astropy Collaboration et al. 2018), scipy (Jones et al. 2001), emcee (Foreman-Mackey et al. 2013), PyNBody (Porter et al. 2016), Matplotlib (Hunter 2007), photutils (Bradley et al. 2017), SpicePy (Annex et al. 2018).

Appendix

The Appendix comprises Table 3.

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Figure 3. Free and forced elements for best-fit 2014 MU₆₉; the centers of the circles show forced inclination/eccentricity, while the radii show free inclination/eccentricity. The forced inclination is 0°26 from the mean solar system angular momentum vector (left), but almost perfectly fits the mean Kuiper Belt at 44 au pole from (Volk & Malhotra 2017, right). The lack of forced eccentricity or inclination implies that MU₆₉ has not experienced any significant orbital evolution since formation.

Table 2

| Best Fit $10^8$ years | 
|----------------------|
| Mean $a$             | 44.23 au |
| Forced $e$           | $6 \times 10^{-5}$ |
| Free $e$             | 0.037 |
| Forced $i_{max}$     | 0°26 |
| Forced $i_{free}$    | 0°0012 |
| Free $i$             | 2°54 |

The Appendix comprises Table 3.
Table 3
HST/WFC3 Astrometry for MU69

| WFC3 Data Set | UTC Time   | R.A.      | Decl.      | σ R.A. (mas) | σ decl. (mas) |
|---------------|------------|-----------|------------|--------------|---------------|
| icii11r7q     | 2014 Jun 26T08:51:42.4042 | 18°45'10"67179 | −20°53'03"0565 | 6.496 | 5.874 |
| icii11r8q     | 2014 Jun 26T09:00:33.4117 | 18°45'10"63684 | −20°53'03"1070 | 8.280 | 8.519 |
| icii11raq     | 2014 Jun 26T09:09:24.4036 | 18°45'10"59521 | −20°53'03"1759 | 9.150 | 9.504 |
| icii11r9q     | 2014 Jun 26T09:18:15.3964 | 18°45'10"55800 | −20°53'03"2431 | 7.130 | 6.348 |
| icii1lreq     | 2014 Jun 26T09:27:06.4048 | 18°45'10"52223 | −20°53'03"3121 | 6.935 | 5.378 |

(This table is available in its entirety in machine-readable form.)

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References
Annex, A., Carcich, B., Badger, T. G., et al. 2018, AndrewAnnex/SpicyPy: SpiceyPy, v2.1.1, Zenodo, doi:10.5281/zenodo.1228513, https://github.com/AndrewAnnex/SpiceyPy
Batygin, K., Brown, M. E., & Fraser, W. C. 2011, ApJ, 738, 13
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bradley, L., Sipocz, B., Robitaille, T., et al. 2017, astropy/photutils, v0.4, Zenodo, doi:10.5281/zenodo.1039309, https://photutils.readthedocs.io/
Braga-Ribas, F., Sicardy, B., Ortiz, J. L., et al. 2014, Natur, 508, 72
Brankin, R. W., Gladwell, I., Dormand, J. R., Prince, P. J., & Seward, W. L. 1989, ACM Transactions on Mathematical Software, 15, 31
Conard, S. J., Azad, F., Boldt, J. D., et al. 2005, Proc. SPIE, 5906, 407
Elliot, J. L., Dunham, E., & Mink, D. 1977, Natur, 267, 328
Elliot, J. L., Dunham, E. W., Bosh, A. S., et al. 1989, Icar, 77, 148
Elliot, J. L., Kern, S. D., Clancy, K. B., et al. 2005, AJ, 129, 1117
Folkner, W. M., Williams, J. G., Boggs, D. H., Park, R. S., & Kuchynka, P. 2014, IPNPR, 196, 1
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Fraser, W. C., Bannister, M. T., Pike, R. E., et al. 2017, NatAs, 1, 0088
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, A&A, 595, A2
Greisen, E. W., Calabretta, M. R., Valdes, F. G., & Allen, S. L. 2006, A&A, 466, 747
Gwyn, S. D. J. 2014, JInst, 9, C04003
Hunter, J. D. 2007, CSE, 9, 90
Jones, E., Oliphant, T., Peterson, P., et al. 2001, SciPy: Open Source Scientific Tools for Python, http://www.scipy.org/
Krist, J. E., Hook, R. N., & Stoehr, F. 2011, Proc. SPIE, 8127, 81270J
Linscott, I., Protopapa, S., Hinson, D. P., et al. 2016, in AAS/DPS Meeting 48 Abstracts, 213.04
Michalik, D., Lindegren, L., & Hobbs, D. 2015, A&A, 574, A115
Nelder, J. A., & Mead, R. 1965, CompJ, 7, 308
Noll, K. S., Grundy, W. M., Chiang, E. I., Margot, J.-L., & Kern, S. D. 2008, in The Solar System Beyond Neptune, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 345
Ortiz, J. L., Santos-Sanz, P., Sicardy, B., et al. 2017, Natur, 550, 219
Petit, J.-M., Kavelaars, J., Gladman, B. J., et al. 2011, AJ, 142, 131
Porter, S. B., Spencer, J. R., Benecchi, S., et al. 2016, in AAS/DPS Meeting 48 Abstracts, 213.04
Silverman, B. W. 1986, Density Estimation for Statistics and Data Analysis (London: Chapman and Hall)
Stern, S. A., Bagenal, F., Ennico, K., et al. 2015, Sci, 350, aad1815
Tchebychev, P. L. 1853, Théorie des mécanismes Connus sous le nom de parallélogrammes (St.-Petersbourg: Imprimerie de l’Académie impériale des sciences)
The Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, arXiv:1801.02634
Volk, K., & Malhotra, R. 2017, AJ, 154, 62