Spin Axis and Physical Property Inversion of Moon-Impactor Chang'e 5-T1 Rocket Body

Tanner Campbell
Department of Aerospace & Mechanical Engineering,
Lunar & Planetary Laboratory,
The University of Arizona

Adam Battle
Lunar & Planetary Laboratory,
The University of Arizona

Bill Gray
Project Pluto

Neil Pearson
Planetary Science Institute

Grace Halferty
Department of Aerospace & Mechanical Engineering,
The University of Arizona

Roberto Furfaro
Department of Systems & Industrial Engineering,
Department of Aerospace & Mechanical Engineering,
The University of Arizona

Vishnu Reddy
Lunar & Planetary Laboratory,
The University of Arizona

ABSTRACT

On March 4, 2022, the object provisionally known as WE0913A crashed into the Moon after several close flybys of the Earth and the Moon in the previous three months. Leading up to impact, the identity of the lunar-impactor was up for debate with two possibilities: the Falcon 9 rocket from the DSCOVR mission or the Long March 3C from the Chang'e 5-T1 mission. Based on forensic astrodynamic astrodynamic and spectral analysis, it has been shown conclusively that WE0913A is the Long March 3C R/B from the Chang'e 5-T1 mission [1]. In this paper we show analysis of photometric light curves collected before impact which give a spin period of 185.221 $\pm$ 6.540 s at a 1σ confidence level just before the first close Earth fly-by on January 20, 2022, and a period of 177.754 $\pm$ 0.779 s at a 1σ confidence level just before the second close Earth fly-by on February 8, 2022. Using Markov Chain Monte Carlo sampling and a predictive light curve simulation based on an anisotropic Phong reflection model, we estimate both physical and dynamical properties of the Chang'e 5-T1 rocket body at the start of an observation epoch. The results from the Bayesian analysis imply that there may have been additional mass on the front of the rocket body.

1. INTRODUCTION

On March 14, 2015, Catalina Sky Survey [2], which scans the sky for near-Earth objects (NEOs), discovered a new object and provisionally named it WE0913A. Additional observations showed that the object previously had a lunar flyby on February 13, 2015. On February 11, 2015, NASA had launched the DSCOVR spacecraft towards the Earth-Sun L1 point on a Falcon 9 rocket from Cape Canaveral, Florida. Consequently, WE0913A was initially linked to the Falcon 9 rocket body (R/B) (NORAD ID 40391, COSPAR ID 2015-007B) which was used for the launch of the DSCOVR mission. The original assumption that this was the DSCOVR R/B was more circumstantial rather than conclusive, and incidentally, the DSCOVR mission did not go particularly close to the Moon post launch. From the analysis shown in [1], we now know conclusively that WE0913A was, in fact, the upper stage of the Long March 3C (NORAD ID 40284, COSPAR ID 2014-065B) which launched the Chang'e 5-T1 mission.

In this paper, we present the results of our characterization efforts using both astrometric and photometric data of WE0913A in order to provide insight into some dynamical and physical properties of the Chang'e 5-T1 rocket body (R/B) which impacted the Moon on March 4, 2022.

2. DATA COLLECTION

The data products used directly in this research are the time history of reduced photometric brightness measurements (light curves) taken from imagery data acquired with each telescope. Astrometric position measurements are only used indirectly, being needed for orbit determination to allow for later trajectory propagation to support the reflective dynamics model [3]. All the imagery data used were collected from a telescope located in Arizona, USA (details in [1]). The observation geometry, dates, and number of images taken can be found in Table 1.

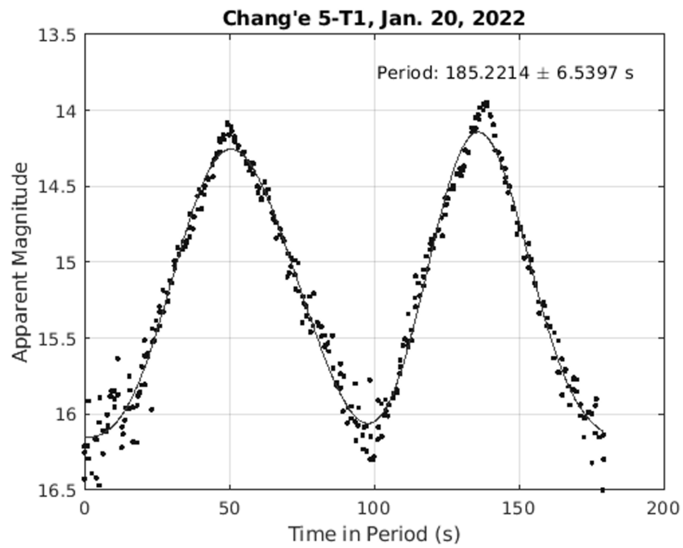
Table 1: Summary of observation epoch and geometry for the collected data.

Name	**Date (UTC)**	**Range (km)**	**V Mag (Pred.)**	**Phase Angle (°)**	**No. of Obs.**
Leo-20	2022/01/20	169,000	15.3	91.4	400
	2022/02/08	144,000	15.2	102.5	300

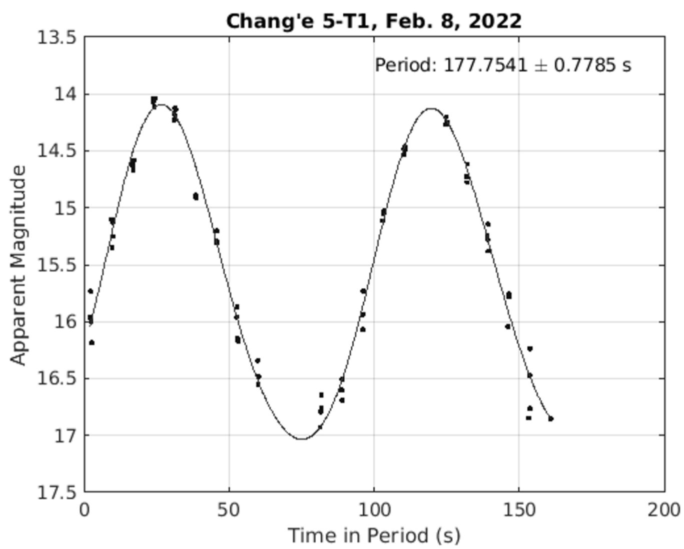
All observations from Leo-20 were taken with an open/clear filter, or using the Sloan Digital Sky Survey (SDSS) g' and r' photometric filters with band passes ($>$ 50% transmission) of 401 - 550 nm and 555 - 695 nm, respectively.

3. PHOTOMETRIC ANALYSIS

The photometric measurements taken on January 20 and February 8, 2022 show a strong apparent periodicity in the light curves of the Chang'e 5-T1 R/B that implies the object is neither actively stabilized nor tumbling (in the complex sense), but rather uniformly rotating (typically) about either its major or minor principal axes of inertia. It is also typical for objects rotating in this manner to then have a precession of this rotational axis about the body's angular momentum vector [4]. To quantify this observed periodicity, we performed a four parameter Fourier fit with least squares minimization to the light curves taken just before each of two sequential close Earth fly-bys. The results of these minimizations are in Figures 1a, 1b.



(a) Data from Leo-20 observatory, Jan. 20, 2022



(b) Data from Leo-20 observatory, Feb. 08, 2022

Fig. 1: Light curves of Chang'e 5-T1 R/B from before each of two sequential close Earth fly-bys taken from the same observatory. The light curves have had been period wrapped by fitting a four parameter Fourier series to the data via least squares minimization. As can be seen by the fitted period in each plot, the observed rotation rate of Chang'e 5-T1 changed substantially between the two fly-bys.

Figures 1a, 1b show that period of the light curve changes between the two observing epochs, indicating a likely change in the rotational period of the Chang'e 5-T1 R/B. While the period of the light curve just before the second Earth fly-by is within the 2σ bounds of the first set of data, the reverse is not true indicating that this is likely a real change in the rocket body's rotational rate. A high-fidelity attitude simulation and analysis may be able to lend insight into the impact of the first Earth fly-by on the Chang'e 5-T1 R/B rotational period, but this is outside the scope of this work.

4. BAYESIAN ANALYSIS AND RESULTS

Bayesian inversion relies heavily on a statistical forward model that can map arbitrary samples in your chosen parameter space to realistic samples in the desired observation space. It is important to strike a good compromise between model fidelity and computational requirements for said model since there are harsh diminishing returns for increased fidelity with ill-posed inverse problems.

Using a predictive light curve model and Markov Chain Monte Carlo (MCMC) sampling-based inversion of astrometric and photometric data collected of the Chang'e 5-T1 R/B during both of its final close approaches with the Earth before impacting the Moon, we recover likely distributions for spin state and reflective properties. We estimate nine parameters: primary body axis orientation (2), angular velocity vector (3), diffusive/specular reflectivity parameters (2), and surface anisotropic/roughness parameters (2). An in-depth discussion of the model used is given in [3].

We ran a total of 100,000 iterations of our MCMC inversion on the data collected with the Leo-20 telescope on January 20, 2022. Our prior distributions for each estimated parameter are partially uninformative in that they are not true (infinite) uniform distributions, but rather finite distributions constrained by what is reasonable for both the model and the physics of the problem. The parameters α and β describe the primary body axis orientation at the start of the observation epoch, w_{1-3} are the angular velocity vector, ρ and F_0 control the relative diffusivity and specularity of the body, respectively. Lastly, n_u and n_v control the amount of anisotropy in each of the body facet directions (see [3] for definitions).

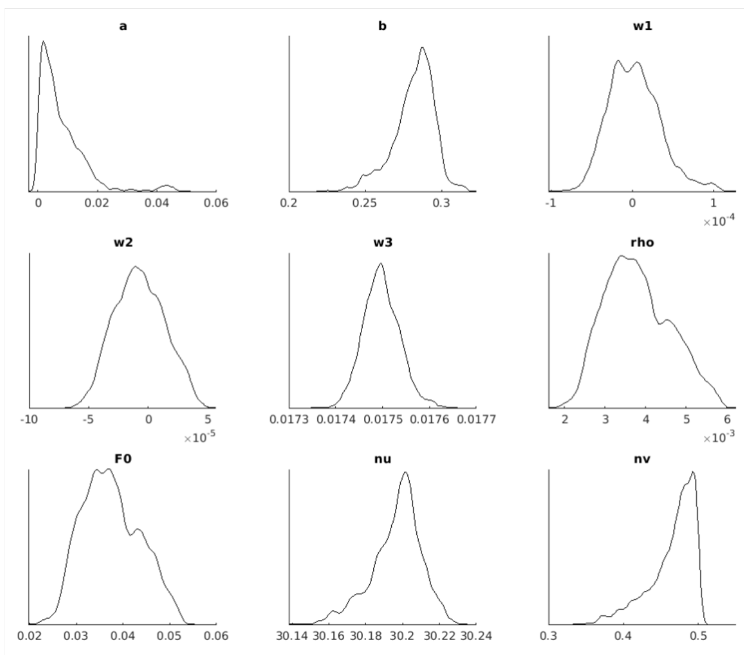


Fig. 2: Final estimates of the posterior distributions of each parameter.

Figure 2 shows diagrams of the posterior distribution estimates for each parameter, and Table 2 summarizes the relevant parameters associated with the distributions for each parameter.

Table 2: Bayesian and frequentist statistics for the estimated posterior distributions of each parameter.

Variable	MAP	95% HPD	Mean	STD
α	0.002	[0.0000, 0.0204]	0.008	0.008
β	0.287	[0.2473, 0.3008]	0.282	0.013
w_1	0.000	[-0.0001, 0.0001]	0.000	0.000
w_2	0.000	[-0.0001, 0.0001]	0.000	0.000
w_3	0.017	[0.0174, 0.0176]	0.017	0.000
ρ	0.004	[0.0025 0.0054]	0.004	0.001
F_0	0.037	[0.0276, 0.0500]	0.037	0.006
n_u	30.203	[30.1695, 30.2221]	30.197	0.013
n_v	0.497	[0.3995, 0.4999]	0.465	0.030

An important distinction for the values provided in Table 2 is the subtle difference between frequentist and Bayesian statistics as they are given here. The frequentist statistics (mean and standard deviation) are indicative of how *often* an event occurs, while the Bayesian statistics (maximum a posteriori (MAP) and highest posterior density (HPD)) provide how *likely* it is that an event occurs, given the data you have and your understanding of the system. Looking at Figure 2 and comparing the values in Table 2 we see that in this case, the estimated distributions for our parameters can be well approximated by Gaussian distributions. This is typically not the case in general, as the estimated distributions from this process can be highly non-Gaussian.

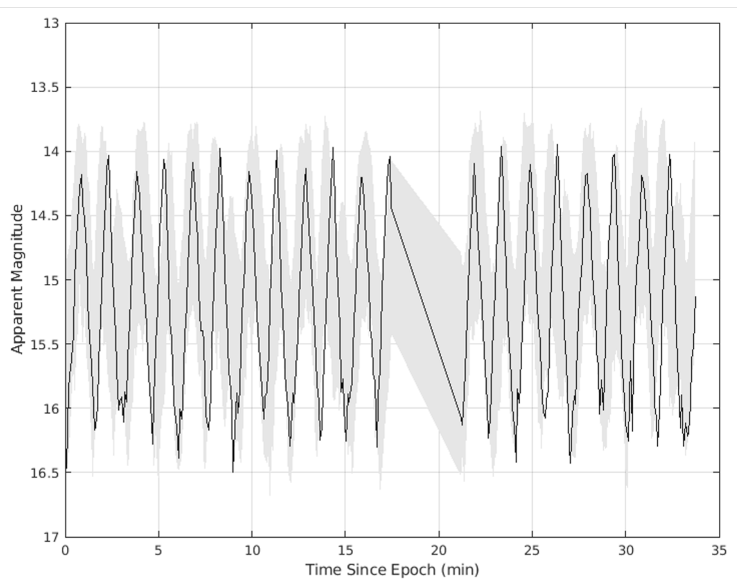


Fig. 3: The 97.5% (light gray) HPD region in light curve phase space as estimated by 1500 random samples from the posterior estimates generated with data taken from the Leo-20 telescope on Jan. 20, 2022. The observed light curve of the Chang'e 5-T1 R/B has been overlaid in black. The diagonal portion of the light curve from approximately 17-21 minutes post-epoch is a period where no data were collected.

Estimating the complete distribution of each parameter gives us not only insight into the global set of possible results but allows sampling from each distribution to evaluate behavior. In Figure 3 we took 1500 random samples from each distribution and fed them back into our forward model. Plotting the results and overlaying the raw Chang'e 5-T1 light curve, we can see that the estimated parameters and forward model fit the data very well. Note that the diagonal portion of the plot between 17- and 21-minutes post-epoch is when there was no data. Since it is possible for the "best estimate" to converge on an incorrect, or poorly fitted solution, evaluating the results in this way offers a self-consistency check and confidence that the estimated parameters well-describe the data.

Based on the values in Table 2, it would appear that the Chang'e 5-T1 RB is very anisotropic (ratio of n_u to n_v). As a reminder these two parameters control the surface roughness and the degree of anisotropic reflection in either the $\hat{\boldsymbol{u}}$ or $\hat{\boldsymbol{v}}$ directions for each body facet (see [3]). In Table 2 we see that the estimated reflection is approximately 60 times greater in the $\hat{\boldsymbol{u}}$ direction than the $\hat{\boldsymbol{v}}$ direction. While it is quite likely that the Chang'e 5-T1 R/B exhibits some anisotropy, this level is unexpected. This is most likely a result of the fact that the observations used for this estimation spanned a short time window, and so geometrically speaking, reflection in the orthogonal axis may not have been as visible. This is further supported by the rotation of the body being that of a very stable spin, implying that body surfaces are observed from the same geometry over short time scales as the body rotates. This is opposed to a complex tumbling body where the observer-target body surface geometry may not be as periodic during rotation.

The strong periodic fits seen in Figures 1a, 1b imply that the Chang'e 5-T1 R/B was in a very uniform spin during the observations. This is reflected in our results by the estimated angular velocity (Table 2). Note that it is almost identically equal to a uniform spin about a single (the principal) body axis. This is somewhat unexpected for a typical rocket body, especially one that has been on-orbit for almost a decade and has had multiple close encounters with the Earth and Moon. In a typical (empty) rocket upper stage, the majority of its mass is concentrated towards the engines, giving an appreciable center-of-mass-center-of-figure (COM-COF) offset. This COM-COF offset can cause perturbations such as solar radiation pressure or gravity gradient torque to have a larger destabilizing effect, giving rise to more complicated motion than just simple spin (i.e. precession, nutation, complex tumble, etc.) [5], which is one possible explanation of the results seen in [3]. However, we see no such evidence for perturbations in the spin of the Chang'e 5-T1 R/B implying that the COM-COF offset may be smaller than expected. This would be the case if there was additional mass at the front of the rocket body, opposite the engines. This additional mass at the front of the body would bring the COM forward, closer to the COF and thus reduce the effect of these destabilizing perturbations.

The Chang'e 5-T1 R/B hosted a secondary payload (in addition to the Chang'e 5-T1 spacecraft) that was comprised of two instruments and dubbed the Manfred Memorial Moon Mission (4M) by LuxSpace [6]. This payload has a published mass of 10-14 kg and was permanently affixed to the front of the Chang'e 5-T1 R/B [7, 6, 8]. It is unclear if, or how, the upper stage was modified to accommodate this payload vis-à-vis structural support or additional equipment that might affect the final mass distribution, however, the published mass of these instruments is only up to 14 kg, which is not enough to appreciably move the COM forward from the large mass of the dual-mounted YF-75 engines on its own [9].

5. CONCLUSIONS

In late 2021, it was discovered that an object (WE0913A) would impact the Moon in March 2022 after several close flybys of the Earth and the Moon over the coming months. The true identify of this object was up for debate with two possibilities: 1) the Falcon 9 R/B from the DSCOVR mission; 2) the Long March 3C R/B from the Chang'e 5-T1 mission. It is now known that WE0913A is in fact the Chang'e 5-T1 R/B. Analysis of photometric light curves gave a spin period of 185.221 ± 6.540 s at a 1σ confidence level of the Chang'e 5-T1 R/B just before the first close Earth fly-by and a period of 177.754 ± 0.779 s at a 1σ confidence level just before the second close Earth fly-by. Using Markov Chain Monte Carlo sampling and a predictive light curve simulation based on an anisotropic Phong reflection model, we estimate both physical and dynamical properties of the Chang'e 5-T1 R/B at the start of an observation epoch. The Bayesian analysis implies that there was an additional mass at the front of the R/B that stabilizes the spin characteristics. The Chang'e 5-T1 R/B hosted a secondary payload that comprised of two instruments with a published mass between 10-14 kg permanently affixed to the front of the rocket body [7, 6, 8]. However, the published mass of these instruments is not enough to appreciably move the COM forward, suggesting the presence of additional mass towards the front of the rocketbody in excess of the published secondary payload mass.

ACKNOWLEDGMENTS

This work is supported in part by the state of Arizona Technology Research Initiative Fund (TRIF) grant (PI: Prof. Vishnu Reddy).

REFERENCES

[1] T. Campbell, A. Battle, B. Gray, N. Pearson, G. Halferty, V. Reddy, and R. Furfaro. Physical Characterization of Moon Impactor WE0913A. *The Planetary Science Journal*, submitted 2023.

[2] E. Christensen, B. Africano, G. Farneth, D. Fuls, A. Gibbs, A. Grauer, H. Groeller, J. Johnson, R. Kowalski, S. Larson, and Others. Status of the Catalina Sky Survey for Near Earth Asteroids. In *AAS/Division for Planetary Sciences Meeting Abstracts# 50*, volume 50, pages 310–10, 2018.

[3] T. Campbell, R. Furfaro, V. Reddy, A. Battle, P. Birtwhistle, T. Linder, S. Tucker, and N. Pearson. Bayesian Approach to Light Curve Inversion of 2020 SO. *The Journal of the Astronautical Sciences*, 69(1):95–119, 2022.

[4] C. Benson, D. Scheeres, and N. Moskovitz. Light Curves of Retired Geosynchronous Satellites. In *7th European Conference on Space Debris*, volume 7, page 04, 2017.

[5] Y. Takahashi, M. Busch, and D. Scheeres. Spin State and Moment of Inertia Characterization of 4179 Toutatis. *The Astronomical Journal*, 146(4):95, 2013.

[6] A. Siddiqi. *Beyond Earth: A Chronicle of Deep Space Exploration, 1958-2016*, volume 4041. National Aeronautis & Space Administration, 2018.

[7] S. Clark. First Commercial Mission to the Moon Launched from China. *Spaceflight Now*, 2014.

[8] H. Moser, G. Ruy, K. Schwarzenbarth, J. Frappé, K. Baessler, and B. Van Schie. Manfred Memorial Moon Mission (4M): Development, Operations and Results of a Privately Funded Low Cost Lunar Flyby. In *29th Annual AIAA/USU Conference on Small Satellites*, number SSC15-V-7, 2015.

[9] Z. Cen, R. Gao, and L. Shen. LM-3A Series Launch Vehicle User's Manual. *China Academy of Launch Vehicle Technology, Beijing*, 2011.