Dimorphos post-impact lightcurves and its new spin state and shape

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Abstract

Dimorphos, the secondary member of the binary asteroid (65803) Didymos, was impacted by NASA's Double Asteroid Redirection Test (DART) spacecraft on September 26, 2022. Its original shape was nearly rotationally symmetric, close to an oblate spheroid, and it was probably in a synchronous spin state. As such, it did not show a detectable secondary brightness variation before the DART impact. During favorable observing conditions in December 2022 and January 2023, we detected significant rotational brightness variations from Dimorphos, with the secondary lightcurve amplitudes (in the total light from the primary and secondary) ranging from 0.008 to 0.031 mag. The data indicate that Dimorphos was either significantly re-shaped by the DART impact or it entered a tumbling spin state after the impact (or both). If Dimorphos is in or close to a synchronous spin state after the impact, then the lightcurve amplitude data suggest its equatorial axis ratio $a/b \sim 1.3$. However, the different secondary lightcurve amplitudes observed at 2 of the 7 epochs suggest that it is likely in a tumbling spin state. A full 2-body dynamics modeling of the post-impact system is needed to obtain constraints on Dimorphos's new spin and shape.

Introduction

On September 26, 2022, NASA's Double Asteroid Redirection Test (DART) spacecraft impacted the satellite, called Dimorphos, of the binary asteroid (65803) Didymos. It was a successful test of Kinetic Impactor technology for diverting dangerous asteroids from a collision course with Earth. Photometric, radar and spectral observations taken from 2003 up to the day of the DART impact and the images taken with the DRACO camera onboard DART led to a description of the binary system at an unprecedented level (Pravec et al., 2022; Scheirich & Pravec, 2022; Naidu et al., 2022; Daly et al., 2023; and references therein). One of the most interesting findings was that Dimorphos had a nearly rotationally symmetric shape, close to an oblate spheroid (Fig. 1). However, the DART impact should have changed its shape (and spin state; Raducan & Jutzi, 2022; Agrusa et al., 2021). We look into that with the highest quality photometric observations that we took in the post-impact apparition in 2022-2023.

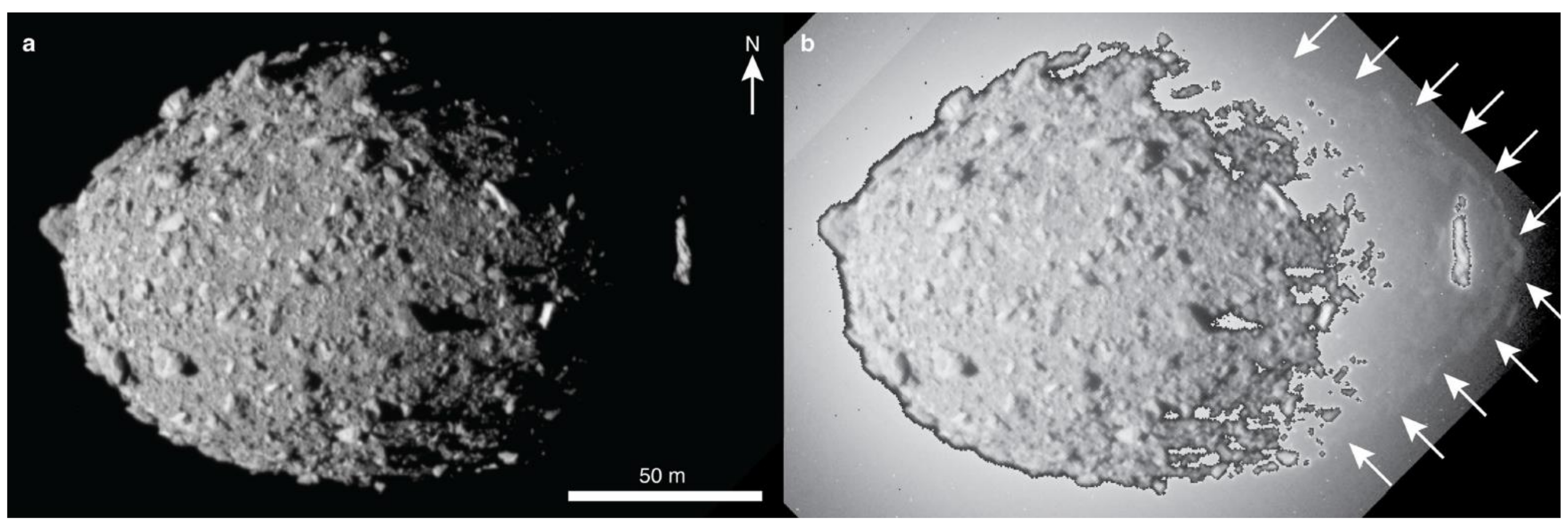

Fig. 1: Sunlit and Didymos-lit limbs of Dimorphos. Together, the two limbs reveal a complete outline of the asteroid as seen by DRACO onboard DART. A regular pre-impact shape of Dimorphos, close to an oblate spheroid, was derived from the images (Daly et al. 2023).

Dimorphos lightcurve observations

Pre-impact observations:

- **No significant secondary rotational amplitude detected**. Consistent with Dimorphos's original shape close to a rotationally symmetric oblate spheroid.

Post-impact observations --- the best data for detecting Dimorphos's lightcurve taken on 7 epochs between 2022-12-14 and 2023-01-29:

- **Secondary rotational lightcurve detected**. Its amplitudes (in the total light from the primary and secondary) were from 0.008 to 0.031 mag. An example of the lightcurve data is shown in Fig. 2.

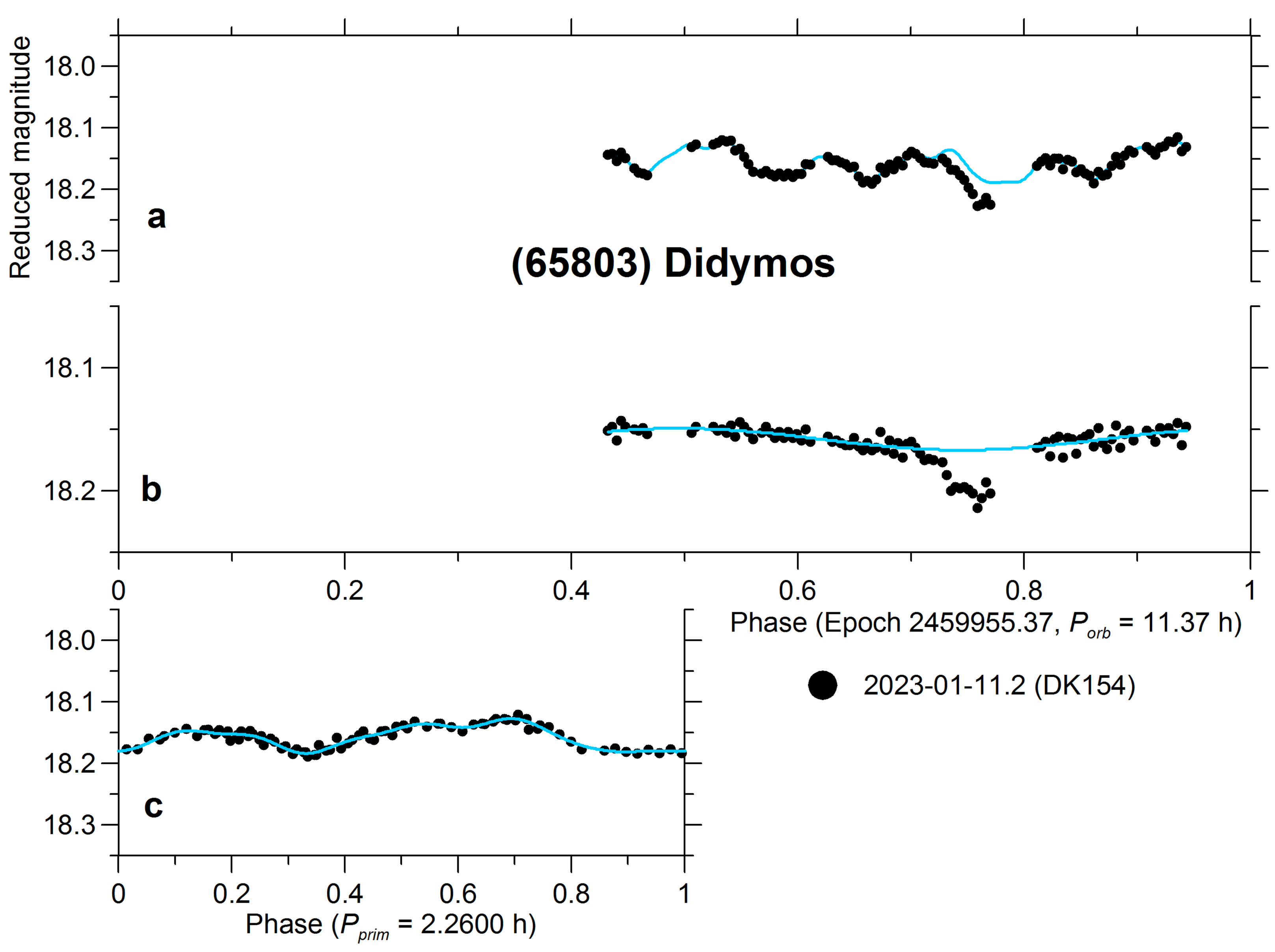

Fig. 2: Decomposition of the Didymos lightcurve data from 2023-01-11. Dimorphos's and Didymos's rotational lightcurves are shown in panels b and c (blue curves). Dimorphos's lightcurve shows the typical feature: its minimum coincides with the mutual event, indicating that the long axis of Dimorphos points approximately to Didymos.

Table 1: Dimorphos lightcurve amplitudes A_{sec} (observed at given solar phase), A_{sec0} (corrected to zero solar phase), and its estimated cross-section variation amplitude ΔC, normalized to the mean cross-section, at the 7 observed epochs.

Epoch	A_{sec} (mag)	Sol.Ph. (deg)	A_{sec0} (mag)	$\Delta C/C_{sec}^{mean}$	Telescope(s)
2022-12-14 to 15	0.022	31.0	0.011	0.12	LDT, Faulkes
2022-12-22	0.018	22.4	0.011	0.12	DK154
2022-12-28 to 31	0.008	14.2	0.006	0.07	DK154, (D65, LCOGT-ELP)
2023-01-11	0.018	6.6	0.015	0.17	DK154
2023-01-14 to 16	0.015	8.2	0.012	0.13	DK154, (LCOGT-ELP)
2023-01-18	0.014	9.8	0.011	0.12	DK154
2023-01-28 to 29	0.031	16.7	0.021	0.24	DK154, MRO

In Table 1, we present parameters measured or estimated from the Dimorphos lightcurves observed at the 7 distinct epochs. The cross-section variation amplitude over a half-rotation (~half orbit period) of Dimorphos is defined as

$C_{sec}^{max} = C_{sec}^{mean} + \Delta C$,

$C_{sec}^{min} = C_{sec}^{mean} - \Delta C$,

where $C_{sec}^{mean} = \pi D_{sec}^2/4$ and D_{sec} is the effective diameter of Dimorphos.

Main observed features

- **Dimorphos's lightcurve minima coincided with the mutual events** (to within a few tens of degrees).
- **The average amplitude of the cross-section variation** (excluding the two outliers that were observed at the epochs 2022-12-28 to 31 and 2023-01-28 to 29): **$\Delta C = 0.13\ C_{sec}^{mean}$**. So, on average, Dimorphos's apparent cross section varied between $0.87 C_{sec}^{mean}$ and $1.13\ C_{sec}^{mean}$ over half of its rotation (i.e., over a half of the orbit period of 11.37 h).
- On 2 of the 7 epochs, the amplitude of the cross section variation was lower ($\Delta C = 0.07\ C_{sec}^{mean}$) or higher ($\Delta C = 0.24\ C_{sec}^{mean}$), suggesting a **change of aspect**.

Possible interpretations

If Dimorphos is not tumbling, then the average $\Delta C = 0.13\ C_{sec}^{mean}$ suggests the equatorial axis ratio $a/b \sim 1.3$. (The 2 outliers being observational errors?) Moderate librations (on the order of a few tens of degrees amplitude) are not ruled out.

If Dimorphos is tumbling, then the maximum observed $\Delta C = 0.24\ C_{sec}^{mean}$ suggests a lower limit on its longest-to-shortest axis ratio $a/c \sim 1.6$. Or, in the case this outlier is an observational error, then the average $\Delta C = 0.13\ C_{sec}^{mean}$ suggests a lower limit on $a/c \sim 1.3$. Full 2-body dynamics modeling of the post-impact Didymos-Dimorphos system is needed to obtain constraints on the current spin state of Dimorphos. First results suggest that the observed changes of Dimorphos's apparent cross-section amplitude over its rotation are due to an attitude instability, showing variations of Dimorphos's obliquity (which is the angle between the Dimorphos's shortest axis *c* and the normal to the mutual orbit plane). However, the fact that the lightcurve minima are approximately aligned with the mutual events suggests that Dimorphos is in an excited tumbling spin state where, on average, it is tidally locked.

Acknowledgements

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