

Revisit of rotational dynamics of Asteroid 4179 Toutatis from Chang'e-2's flyby

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Abstract. This paper presents analysis of the rotational parameters of Toutatis based on the observational results from Chang'e-2's close flyby. The 3-D shape model derived from ground-based radar observation is used to calculate the 3-1-3 Euler angles at the flyby epoch, which are evaluated to be $-20.1^\circ \pm 1^\circ$, $27.6^\circ \pm 1^\circ$ and $42.2^\circ \pm 1^\circ$. The large amplitude of Toutatis' tumbling attitude is demonstrated to be the result of the large deviation of the angular momentum axis and the rotational axis. Two rotational periods are evaluated to be 5.38 ± 0.03 days for rotation about the long axis and 7.40 ± 0.03 days for precession of the long axis about the angular momentum vector based on Fourier analysis. These results provide a further understanding of rotational state of Toutatis.

Keywords. minor planets, asteroids

1. Introduction

Near Earth asteroid 4179 Toutatis is an Apollo-type object and categorized as a potentially hazardous asteroid (PHA). It has a highly eccentric orbit, approximately 4:1 resonant with the Earth. It was firstly discovered in 1934 and the rediscovery took place in 1989. It has closely encountered the Earth every four years during the last decade, enabling a variety of ground-based assessments. Radar observations generated by Arecibo and Goldstone reveal the irregular shape with two lobes and the tumbling, non-principal axis (NPA) rotating state of the asteroid (Ostro *et al.* 1995; Hudson *et al.* 1998; Ostro *et al.* 1999, 2002; Hudson *et al.* 2003). Spencer *et al.* (1995) calculated two rotational periods of the complicated spin state, which were 7.3 and 3.1 days using optical data acquired during 1992 flyby. Meanwhile, they were determined to be 5.41 days and 7.35 days based on radar observations (Hudson *et al.* 1995). Ostro *et al.* (1995) pointed out that this tumbling rotation may be primordial. Ostro *et al.* (1999) used 1996 near-Earth approach radar observations to determine the two major rotational periods, which were estimated to be 5.376 ± 0.001 days and 7.420 ± 0.005 days. Takahashi *et al.* (2013) established a dynamical model of rotation and calculated the spin state parameters using radar observations during five flybys from 1992 to 2008.

The first space-based optical observation of Toutatis was obtained by the second Chinese lunar probe Chang'e-2 at a distance of 770 ± 120 (3σ) meters at the end of 2012 (Huang *et al.* 2013). Over 400 images were captured during the outbound flyby, through which we estimated Toutatis' orbit, dimensions and orientations.

2. Methods and Results

The three-dimensional shape model derived from radar observations (Busch *et al.* 2012), as shown in Figure 1a, is used to match the optical image acquired by Chang'e-2

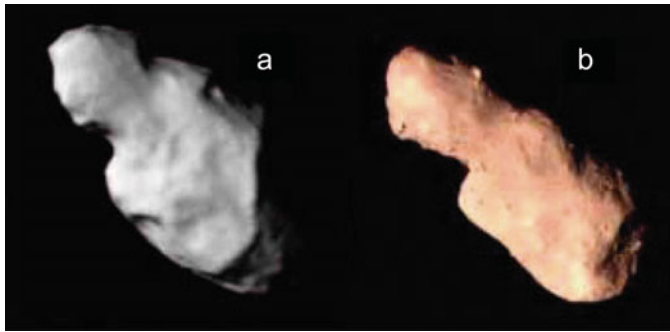


Figure 1. Images of Toutatis. a: Best-matching attitude of the radar model with the optical image. b: First panoramic image captured by Chang'e-2.

(Figure 1b) and calculate the Euler angles at the flyby epoch (Zhao *et al.* 2015, 2014a). Taking the camera's orientation, the Sun-asteroid-spacecraft angle and render situations into accounts, we rotate the radar shape model about its principal axes at a interval of 1° for each of the three Euler angles and use image matching procedure to obtain the orientation parameters. The simulated Euler angles are

$$\vec{R} = R_z(42.2^\circ)R_x(27.6^\circ)R_z(-20.1^\circ)\vec{r}. \quad (2.1)$$

In combination with radar observations during 1992-2008 (Takahashi *et al.* 2013), we use the least-squares method to simulate evolution of rotational dynamics of Toutatis. The external gravitation torques exerted by the Sun, the Earth and the Moon were taken into consideration to establish the rotational dynamical model. The simulated residuals of spin parameters were normalized with respect to the radar observational errors and they all located in 3σ region.

Our simulation results reveal that the orientation of angular momentum axis could be indicated by $(\lambda_H = 180.2_{-0.3}^{+0.2}^\circ$ and $\beta_H = -54.75_{-0.10}^{+0.15}^\circ)$ in the ecliptic coordinate system, which has remained nearly unchanged in space over the past two decades. Figure 2 shows the variation of longitude and latitude of this orientation due to distance from the Sun for the past more than twenty years, the variation amplitudes are less than one degree in both cases. The slight misalignment of both curves is led by the 2004 near-Earth flyby at a distance of about 4 Earth-Moon distance. The precession amplitude is determined to be approximately 60° , which results in significantly different attitudes observed from the Earth at different epochs.

Amplitudes of external gravitation torques and the resulted momentum variations are also simulated in our calculation (Zhao *et al.* 2015, 2014b) see also Ji *et al.* 2015, this volume). Solar tides plays the most important role in the past two decades and near Earth flybys always led to slight changes.

By applying Fourier transform, the latitudinal variations of the asteroid's long and middle axes in the J2000 ecliptic frame (as Figure 3 shows) is simulated to determine the two rotational periods, which are 5.38 days for the rotation and 7.40 days for precession (Zhao *et al.* 2015). These results are in good agreement with the previous results reported by Ostro *et al.* (1999).

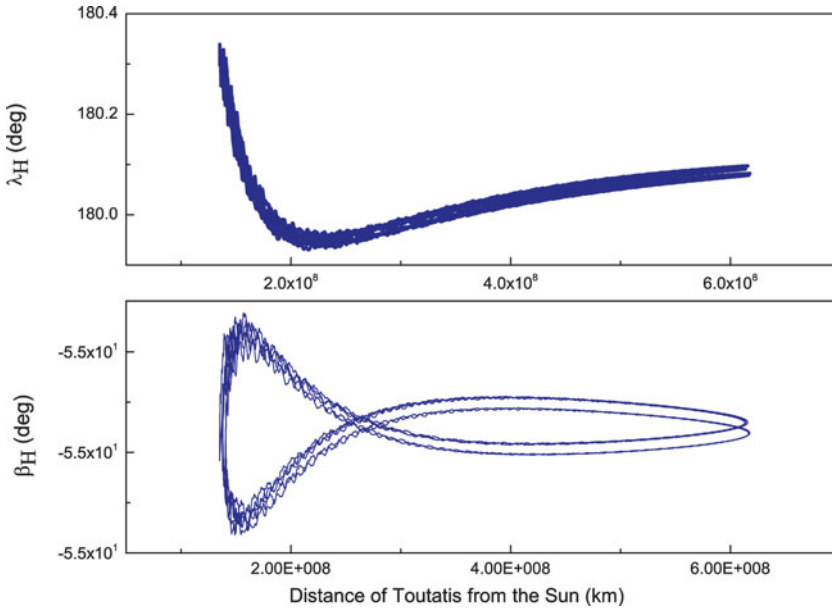


Figure 2. Variations in Toutatis' angular momentum orientation from 1992 to 2012. The two panels show the change in longitude (upper) and latitude (lower) with the distance of Toutatis from the Sun.

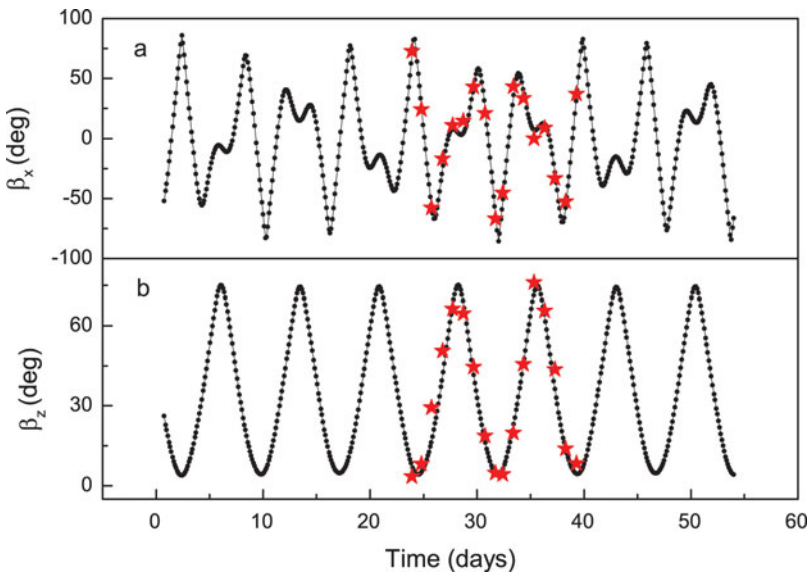


Figure 3. Latitudinal variations of Toutatis' long axis β_z (upper) and middle axis β_x (lower) in the J2000 inertial coordinate system in 1992 (reproduced from Zhao *et al.*, 2015).

3. Conclusions and Discussions

In this work, we used three-dimensional shape model derived from radar observations to establish the transformation relations between inertial frame, body-fixed frame, spacecraft frame and instrument's frame. Then we obtained a 3-1-3 Euler angles of the conversion matrix from the celestial coordinate to the body-fixed frame, which are $-20.1^\circ \pm 1^\circ$, $27.6^\circ \pm 1^\circ$ and $42.2^\circ \pm 1^\circ$. The angular momentum orientation is determined

to be $\lambda_H = 180.2_{-0.3}^{+0.2}^\circ$ and $\beta_H = -54.75_{-0.10}^{+0.15}^\circ$, which is considered to be unchanged for the past two decades. Fourier analysis is used to obtain the two major rotational periods, which are 5.38 ± 0.03 and 7.40 ± 0.03 days, respectively. Our work provides further investigation of the rotational dynamics of Toutatis.

Acknowledgements

This work is financially supported by National Natural Science Foundation of China (Grants No. 11303103, 11273068, 11473073), the Strategic Priority Research Program-The Emergence of Cosmological Structures of the Chinese Academy of Sciences (Grant No. XDB09000000), the innovative and interdisciplinary program by CAS (Grant No. KJZD-EW-Z001), the Natural Science Foundation of Jiangsu Province (Grant No. BK20141509), and the Foundation of Minor Planets of Purple Mountain Observatory.

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