AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202306.00356

Post-print on the Current Status of Observational Studies of the Asteroid YORP Effect

Authors: Tian Jun[1],[2], Zhao Haibin[1],[3]

Date: 2023-06-07T00:00:00+00:00

Abstract

The YORP effect arises from the net torque generated by differential local recoil forces on irregularly shaped asteroids under solar radiation, and its long-term action can alter the rotational state of asteroids. Starting from the scientific significance and research overview of the asteroid YORP effect, this work elaborates on the importance of the YORP effect for asteroid evolution and provides a detailed introduction to the theoretical foundations and current observational research status of the asteroid YORP effect. Currently, the YORP effect has been observationally confirmed for only six asteroids, with the calculated YORP-driven rotational accelerations indicating that all are in a state of spin-up. In the future, YORP-driven rotational acceleration may be measured through observations for fifteen asteroids. Finally, methods for selecting observable candidates using asteroid photometric data and other information are discussed.

Full Text

Preamble

ChinaXiv Cooperative Journal, Vol. 39, No. 3

September 2021

PROGRESS IN ASTRONOMY Vol. 39, No. 3, Sept., 2021
doi: 10.3969/j.issn.1000-8349.2021.03.01

Observational Studies of the YORP Effect for Small Asteroids

TIAN Jun[1],[2], ZHAO Hai-bin[1],[3]
(1. Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023;
2. University of Science and Technology of China, Hefei 230026;
3. CAS Center for Excellence in Comparative Planetology, Hefei 230026)

Abstract: The YORP effect arises from the net torque produced by differential recoil forces on irregularly shaped asteroids under solar radiation, which can alter asteroid rotation states over long timescales. Beginning with the scientific significance and research overview of asteroid YORP effects, this paper elaborates on the importance of YORP effects for asteroid evolution and provides a detailed introduction to the theoretical foundations and current observational research status. To date, only six asteroids have had their YORP effects observationally confirmed, with measured YORP-driven rotational accelerations all indicating spin-up states. In the future, rotational accelerations driven by YORP may be measured for fifteen additional asteroids. Finally, we discuss methods for selecting observable candidate bodies using asteroid photometric data and other information.

Keywords: asteroids; YORP effect; shape inversion model; thermophysical model
CLC number: P185.7
Document code: A

1 Introduction

Asteroids preserve information from the early solar system and serve as living fossils for studying planetary evolution. The YORP effect plays a crucial role in asteroid evolutionary history. Statistical studies of asteroid rotation characteristics reveal that the spin rate distribution of asteroids smaller than 40 km deviates from a Maxwellian distribution, particularly for near-Earth asteroids which exhibit a clear bimodal structure inconsistent with collisional models. The YORP effect provides a reasonable explanation for this rotational distribution [?]. In 2011, Scheeres et al. [?] proposed that YORP is also an effective mechanism for altering asteroid size distributions. By 2014, Jacobson et al. [?] demonstrated that the current size distribution of main-belt asteroids cannot be explained by pure collisional models, but matches observations well when YORP effects are incorporated. Therefore, in-depth study of the YORP effect represents an important pathway to understanding asteroid evolution and provides crucial insights into solar system evolution.

Recent space missions to asteroids have made direct YORP measurements possible. Close-proximity observations provide high-precision measurements of asteroid size, shape, and rotation, greatly advancing YORP research. In 2003, Japan's Hayabusa mission successfully measured the YORP-driven rotational acceleration of near-Earth asteroid (25143) Itokawa during its exploration [?]. In 2019, NASA's OSIRIS-REx (Origins Spectral Interpretation Resource Identification Security Regolith Explorer) mission also directly measured the YORP-driven rotational acceleration of (101955) Bennu [?].

Near-Earth asteroids pose threats to Earth and human civilization, and their origin, evolution, and high-precision impact risk assessment are closely related to YORP effects. Yarkovsky and YORP effects (including orbital YORP) are important mechanisms for migrating small asteroids from the main belt to near-Earth orbits. In studies of (99942) Apophis's Earth impact risk, Vokrouhlický et al. [?] found that orbit changes driven by Yarkovsky/YORP effects on short timescales are already measurable with current astrometric techniques. Therefore, Yarkovsky/YORP effects can no longer be neglected when precisely measuring the orbital evolution of potentially hazardous asteroids.

YORP effect research can constrain asteroid physical properties such as density and cohesion. In 2018, Scheeres et al. [?] investigated the correlation between rubble-pile asteroid disruption under YORP effects and physical properties including density and cohesion, providing disruption timescales associated with different physical characteristics. Studying YORP effects in asteroid binary systems can constrain the structural strength of rubble-pile asteroids. Constraining asteroid physical parameters through YORP effects will find increasing application.

The YORP effect may also be a mechanism for surface material migration on asteroids. In 2018, Kevin et al. [?] proposed that YORP is an effective mechanism for resurfacing asteroids, simulating the evolution of asteroid spectral slopes and explaining the high abundance of Q-type asteroids. Under YORP-driven spin-up, material at mid-latitudes migrates toward the equatorial region, forming an "equatorial ridge" as seen on Bennu and Ryugu. In 2020, Cheng et al. [?] demonstrated through dynamical simulations that the YORP effect is a key mechanism for equatorial ridge formation. However, also in 2020, Michel et al. [?] discovered ancient craters in Bennu's equatorial region, suggesting the ridge may have existed before crater formation. In summary, the precise role of YORP effects in asteroid surface shape evolution requires further investigation.

YORP effects are also among the triggering mechanisms for active asteroids. In 2019, asteroid (6478) Gault suddenly developed two tails. Kleyna et al. [?] analyzed the particle size distribution in these tails using dust dynamics models (Finson-Probstein approach), concluding that Gault's dust ejection was caused by YORP effects. In March 2019, OSIRIS-REx observed particle ejection events from Bennu's surface, classifying Bennu as an active asteroid. Research into YORP-triggered particle ejection mechanisms is ongoing [?].

In 2019, Veras et al. proposed that YORP effects may play a critical role in the evolution of star-planet systems, particularly during the giant branch phase that main-sequence stars must traverse en route to becoming white dwarfs. YORP effects can cause smaller planets and asteroids to disintegrate into "YORP debris disks" (located 2–100 AU from the stellar center) [?]. This phenomenon is common in the evolution of asteroid disks around giant branch stars. In 2020, Veras et al. [?] suggested that metal pollution in white dwarfs is also caused by asteroid disruption and calculated the timescales for YORP disk existence [?]. Currently, only a few studies have examined asteroids orbiting giant branch stars, representing an important future direction for stellar system evolution research.

Recent years have seen significant progress in combining YORP effects with asteroid observational data, which this paper emphasizes. Section 2 introduces the theoretical foundations of YORP effects. Section 3 presents direct detection of YORP effects using asteroid examples. Section 4 discusses statistical studies of asteroid rotation period and spin axis orientation distributions under YORP effects, including a parameterized statistical method. Section 5 examines YORP selection models and the influence of asteroid surface microstructure, thermal-infrared beaming effects, and global self-heating effects on YORP. Finally, we summarize and provide an outlook.

2.2 Principles and Assumptions of YORP Effects

The principle of YORP effects is illustrated in Figure 1 [Figure 1: see original paper]. An asteroid's irregular shape leads to non-uniform reflection and thermal re-radiation of sunlight across its surface. The recoil forces from this non-uniform radiation create a net torque on the asteroid. Although this torque is extremely small, its long-term cumulative effect can significantly alter the asteroid's rotation state. Direct absorption of solar radiation also produces torque, but this does not create long-term effects under rotation and revolution [**?**].

Generally, two important fundamental assumptions underlie YORP effect studies: Rubincam's zero thermal relaxation approximation and the assumption that asteroids rotate about their principal axes of inertia [**?**]. The zero thermal relaxation approximation is not applicable to meter-scale and smaller asteroids where thermal inertia effects become significant. The principal axis rotation assumption is universally applicable. For asteroids in non-principal axis rotation states or spin-orbit resonance, YORP effects are no longer a dominant factor and are not discussed here [**?**]. Section 2.3 details the YORP torque calculation models for irregularly shaped asteroids.

2.3 YORP Torque Calculations

YORP effects are highly sensitive to asteroid shape, making accurate shape modeling a prerequisite for torque calculations. Triangulation methods are typically used to construct asteroid shapes, calculating YORP torque by summing contributions from individual triangular facets.

Breiter et al. [**?**] presented YORP torque calculation formulas in the local solar frame (LSF), with the facet center as origin, axis z as the outward normal direction, axis x pointing toward the intersection of the meridian with the sun and horizon, and axis y completing the right-handed coordinate system. Let **s** be the unit vector pointing to the Sun and **n** be the unit vector pointing to the zenith. For facet i, the incident flux is , representing the portion of solar radiation absorbed by the facet. Defining irradiance as the ratio of incident flux in any direction to facet area, the irradiance of facet i is [**?**]:

$$\mathrm{E}(\mathbf{s}) = \mathbf{J}\mathbf{s} \quad \mathbf{n}.$$

To account for topographic shading, we introduce a visibility function , which equals 1 if facets are unobstructed and 0 otherwise; J is the collimated radiation density. The reflected ray vector **o** from a facet is expressed as:

$$\mathbf{o} = [1 - \ {}^{2} \cos\ \ , 1 - \ {}^{2} \sin\ \ ],$$

where is the cosine of zenith distance and is azimuth angle. The reflected radiance L from facet dS reflected into solid angle dΩ is:

$$\mathrm{L}\ (\mathbf{o}) = (\ \ \mathrm{dS}\ \mathrm{d}\Omega)^{-1}.$$

Introducing the bidirectional reflectance distribution function f (**s**, **o**), we obtain:

$$\mathrm{L}\ (\mathbf{o}) = \mathrm{f}\ (\mathbf{s}, \mathbf{o})\mathrm{E}(\mathbf{s}).$$

For thermal re-radiation L from the solar system, similarly:

$$\mathrm{L}\ (\mathbf{o}) = (\ \ \mathrm{dS}\ \mathrm{d}\Omega)^{-1}.$$

Assuming L and L have the same direction, we get:

$$\ (\mathbf{o}) = \mathrm{L}\ (\mathbf{o})\ /\ \mathrm{L\_b}(\mathbf{o}),$$

where L_b(**o**) is blackbody emission radiance, so L (**o**) is expressed as:

$$\mathrm{L}\ (\mathbf{o}) = \ (\mathbf{o})\sigma \mathrm{T}^{4}.$$

The radiation recoil force on unit facet dS in unit solid angle dΩ is:

$$\mathrm{d}\mathbf{F} = \text{-}\mathrm{d}^{2}(\ \ +\ \ )\mathbf{o}\ /\ (\mathrm{dS}\ \mathrm{d}\Omega\ \mathrm{c}) = -\ \ \mathrm{L}(\mathbf{o}).$$

Let Ω^{+} denote the sunlit surface and Ω the entire surface. Integrating over the sunlit area, the force expression per unit facet is:

$$\mathrm{d}\mathbf{F} = \text{-}\mathrm{E}(\mathbf{s})\ \ \_\Omega^{+}\ \ \ \mathrm{f}\ (\mathbf{s}, \mathbf{o})\ \mathbf{o}\ \mathrm{d}\Omega\ \text{-}\ 2\sigma \mathrm{T}^{4}\ \mathbf{n}\ \ {}_{0}^{1}\ \ {}^{2}\ \ (\ )\ \mathrm{d}\ .$$

The total torque is:

$$\mathbf{M} = \ \ \_\mathrm{S}\ (\mathbf{r} \times \mathrm{d}\mathbf{F})\ \mathrm{dS},$$

where **r** is the position vector from the asteroid's center of mass to facet dS. Equation (10) shows that asteroid torque is primarily influenced by **r** representing shape and factors related to radiation flux and thermal-physical properties. Mature modeling methods exist for shape representation, including polyhedron methods and particle swarm approaches [**?**], making **r** calculations straightforward, while calculations related to thermal-physical properties have larger errors.

YORP effects influence asteroid spin rate, spin axis obliquity, and precession, though the precessional effect is small and typically neglected. In 2007, Nesvorný et al. [**?**] provided formulas for YORP-induced changes in spin rate and obliquity, establishing a body-fixed coordinate system with origin at the center of mass (COM), axis z as the rotation principal axis, and axis x aligned with the minimum moment of inertia axis. With **r** and **n** defined as before, the

Sun-pointing vector becomes $\mathbf{n}_0$, and and represent asteroid longitude and latitude. For asteroids neglecting thermal inertia, the total torque is:

$$\mathbf{M} = \text{-}\alpha \ \ \text{\_S dS} \ (\mathbf{r} \times \mathbf{n}) \ (\mathbf{n} \ \ \mathbf{n}_0),$$

where α = 2F (1 - p)/(3 c), F is solar radiation flux at the asteroid, p is albedo, c is the speed of light, and surface occlusion is not considered. Let $\mathbf{n}$ dS = $\mathbf{N}$ = $\mathbf{N}$ (dΩ / sin), where the tangential vector $\mathbf{N}$ = $\mathbf{r}$/ × $\mathbf{r}$/ . Equation (11) becomes:

$$\mathbf{M} = \text{-}\alpha \ \ \text{\_S sin} \ \ (\mathbf{r} \times \mathbf{N}) \ \max(0, \mathbf{n} \ \ \mathbf{n}_0).$$

Let r = r_0(1 + R), where R describes surface shape deviation from a standard sphere. Then:

$$\mathbf{r} \times \mathbf{N} = \ \ r_0 \ r^2 \ \mathbf{T},$$

$$\mathbf{T} = [\text{R\_ cos cos + R\_ sin sin , R\_ sin cos - R\_ cos sin , -R\_ sin }],$$

where R_ and R_ are partial derivatives of R with respect to and . $\mathbf{r} \times \mathbf{N}$ can be expanded as a Taylor series:

$$\mathbf{r} \times \mathbf{N} = \ \ r_0{}^3 \ \mathbf{T} \ (1 + 2 \text{ R}) + O({}^3).$$

Let max(0, $\mathbf{n}$ $\mathbf{n}_0$) = I, representing facet irradiance, and $\bar{I}$ denote average irradiance:

$$\bar{I} = \bar{I}_0 + \ \bar{I}_1 + O({}^3),$$

where $\bar{I}_0$ represents average irradiance for a standard sphere and $\bar{I}_1$ is the first-order correction from non-spherical shape.

In 2007, Nesvorný et al. [?] reformulated YORP torque calculations, with the rotational component:

$$\mathbf{M}\text{\_s} = \text{-}\alpha \ r^3 \ \ \text{\_S sin} \ \ [\bar{I}_0 + \ \ \text{sin} \ \ \bar{I}_1 + 2\text{R T\_z } \bar{I}_0] \ d\Omega,$$

where T_z is the z-component of $\mathbf{T}$. The first term in Equation (17) is first-order:

$$\mathbf{M}\text{\_s\^{}(1)} = \text{-}\alpha \ r^3 \ \ \text{\_S sin} \ \ \bar{I}_0 \ \text{T\_z} \ d\Omega.$$

Since $\bar{I}_0$ is independent of and T_z = -R_ sin , calculation yields:

$$\mathbf{M}\text{\_s\^{}(1)} = \text{-}\alpha \ r^3 \ \ \text{\_S } \bar{I}_0 \ \text{R\_} \ \ d\Omega = 0.$$

Thus the first-order term of the YORP torque rotational component vanishes; similarly, the second term of the second-order component also equals zero. Therefore, the YORP rotational component is:

$$\mathbf{M}\text{\_s} = \mathbf{M}\text{\_s\^{}(2)} = \text{-}\alpha \ r^3 \ \ \text{\_S sin} \ \ \bar{I}_1 \ \text{T\_z} \ d\Omega.$$

The YORP torque rotational component is a second-order term, hence YORP is called a "second-order non-gravitational effect" [?]. The YORP rotational acceleration can be written as [?]:

dω/dt = M_s / C.

The change in asteroid spin axis obliquity under YORP effects is:

d /dt = M_ / (C ω sin),

where C is the principal axis moment of inertia, ω is angular velocity, and is spin axis obliquity. Notably, the Legendre second-order term appearing in the derivation of the YORP torque rotational component is:

P_2(cos) = (3 cos^2 - 1)/2.

When 54.7° and 125.3°, the YORP torque rotational component equals zero. These obliquities are close to the axis orientations in the Slivan states of the Koronis asteroid family [?].

In small body orbital evolution, Yarkovsky/YORP effects must be considered alongside collisions, gravitational perturbations, and jet recoil effects. Table 1 compares non-gravitational effects with gravitational perturbations. Over the past two decades, high-precision astrometric and photometric measurements of small bodies have further revealed the importance of Yarkovsky/YORP effects for their dynamical evolution.

Table 1 Comparison of perturbation magnitudes for asteroids 10 cm–10 km

Effect	Radial Acceleration	Tangential Acceleration
Gravitational perturbation	GM /r^2 10^{-7}–10^{-11}	10^{-8}–10^{-12}
Yarkovsky/YORP effect	10^{-6}–10^{-11}	10^{-8}–10^{-12}
Poynting-Robertson effect	10^{-10}–10^{-15}	$<10^{-15}$
Solar wind, Lorentz force, plasma drag	$<10^{-15}$	$<10^{-15}$

In 2006, William et al. [?] noted that for asteroids smaller than 40 km, YORP effects dominate over collisions in influencing dynamical states because YORP evolution timescales are shorter than collisional timescales [?]. Statistical analysis shows [?] that YORP effects are more pronounced for asteroids smaller than 15 km. Direct YORP detection should target asteroids under 15 km [?] without jets or significant cometary activity. Collisional timescales for this size range are 10–100 Myr.

Besides jets and collisions, four other non-gravitational effects exist. Radiation pressure from sunlight and other radiation particles striking the surface produces zero net torque [?]. The Poynting-Robertson effect is a Sun-radiation-induced force opposite to dust particle motion, primarily affecting 1 m–1 mm particles [?]. Solar wind, Lorentz forces, and plasma drag significantly affect 5–100 m charged dust particles [?]. As shown in Table 1, these latter two effects are 3–5 orders of magnitude weaker than Yarkovsky/YORP effects for 10 cm–10 km asteroids. Although Yarkovsky/YORP forces are weak compared to gravitational perturbations, their long-term action significantly affects asteroid rotation states and dominates dynamical diffusion in asteroid families [?], making them the primary non-gravitational driver of asteroid evolution.

2.4 Other Types of YORP Effects

YORP effects are also important mechanisms for forming binary and multiple asteroid systems. The YORP effect experienced by binary asteroids during evolution is called the BYORP effect, first proposed by Ćuk et al. [?]. In 2010, McMahon et al. [?] refined BYORP detection techniques and developed an analytical BYORP model, first applied to asteroid 1999 KW4 [?]. BYORP analysis treats the binary asteroid as a whole and calculates mean motion deviation:

a $\Delta M = -3/2\ (\Delta P/P)$,

where ΔP is the orbital period deviation. Pravec [?] listed potential binary asteroids with mean motion deviations in the BAP (binary asteroid parameters) database. BYORP effects can alter binary system orbital configurations. In binary systems with secondary-to-primary mass ratios >0.2 and in synchronous rotation states, BYORP effects cause contraction or expansion. In 2014, Taylor et al. [?] noted that migration only stops when BYORP effects balance tidal forces, with minimal tidal dissipation. Detailed studies of doubly synchronous systems contracting under BYORP effects leading to disruption and mutual separation are lacking. For systems with mass ratios <0.2, the stable state is typically a single synchronous state where the secondary is tidally locked while the primary spins up. If the secondary's BYORP effect is negative, the system contracts over long timescales; if positive, the system expands, aligning with tidal evolution and eventually losing synchrony. Beyond orbital effects, BYORP influences orbital plane orientation, causing binary system pole drift [?].

In 2014, Jacobson et al. [?] identified BYORP effects as key mechanisms for forming wide asynchronous binary systems. Among nine observed wide asynchronous binaries, six had primary rotation periods near critical spin rates, suggesting YORP effects may be the main formation cause.

In 2011, Jacobson et al. [?] proposed equilibrium between BYORP and tidal forces, enabling determination of tidal dissipation within rapidly rotating primaries for known BYORP-offset binary systems, thereby constraining physical parameters like mechanical strength of rubble-pile asteroids. Steinberg et al. [?] suggested BYORP and YORP effects are positively correlated and described orbital inclination evolution of binary systems under BYORP.

Rubincam et al. [?] proposed that "orbital YORP effects" can cause orbital drift. For asteroids with north-south shape asymmetries, orbital eccentricity prevents cancellation of recoil forces over one orbital period, altering semi-major axis and eccentricity. Thermal inertia reduces orbital YORP effects; higher albedo decreases infrared radiation, reducing thermal inertia effects and increasing orbital YORP. Rubincam et al. [?] noted that orbital YORP effects on Apophis produce orbital changes comparable to Yarkovsky effects. Orbital YORP only significantly affects asteroids with high albedo, slow rotation, and spin axes neither perpendicular nor parallel to the orbital plane. After YORP spin-down, orbital YORP effects become more pronounced and must be considered when studying long-term impact risks of near-Earth asteroids.

"Tangential YORP effect" (TYORP) arises from recoil forces parallel to the surface caused by sub-meter-scale surface protrusions [?]. On asteroids with numerous surface protrusions, TYORP magnitudes can be comparable to YORP effects [?]. TYORP accelerates asteroid rotation and is considered an important reason for the absence of YORP-decelerated asteroids.

3 Direct Detection of YORP Effects

This section introduces direct detection methods for YORP effects. Asteroid spin axis obliquity evolution is complex and difficult to detect directly, so direct detection primarily calculates YORP rotational acceleration. Current methods rely on two models: lightcurve shape inversion models and thermophysical models.

3.1 Shape Inversion Models Based on Lightcurves

Building asteroid shape models from lightcurves primarily uses dense time-series photometric data from multiple apparitions at various phase angles; recently, sparse photometric data have also been applied as supplementary data. Ďurech et al. [?, ?] established and continuously update the Database of Asteroid Models from Inversion Techniques (DAMIT).

Asteroid shapes are based on three fundamental models: triaxial ellipsoid, convex hull, and non-convex models [?]. To better represent shape details, triangulated facets based on Gaussian sphere models are used. Selecting appropriate scattering models (typically Lommel-Seeliger) and summing flux from each facet yields synthetic lightcurves [?].

Fourier analysis determines the synodic period T_{synodic} [?], from which the rotational period T_{rotational} is calculated:

T_{synodic} = T_{rotational} $(1 + (\mathrm{Le}_2 - \mathrm{Le}_1)/\Delta\mathrm{Le})$,

where $(\mathrm{Le}_2 - \mathrm{Le}_1)$ is the projection of observer line-of-sight changes in right ascension [?].

Spin axis orientation can be determined through: (1) lightcurve amplitude using least-squares fitting for pole coordinates, or (2) spin axis direction from rotational period using stellar period and inversion methods to scan for optimal coordinates validated within error bounds.

Shape inversion models from lightcurves yield important physical parameters including shape, rotational period, and ecliptic pole coordinates. The core detection concept involves generating synthetic lightcurves under both constant-period and linearly-varying-period conditions using the inverted shape, then optimally fitting to observed lightcurves. If the latter fits significantly better, the optimal linear period change yields the corresponding YORP rotational acceleration [**?**, **?**].

Two processing approaches exist. First, fixing the rotation period and calculating phase offsets between synthetic and observed lightcurves. The phase offset ϕ from YORP effects relates to time t as:

$$\phi(\mathrm{t}) = \phi_0 + \omega_0(\mathrm{t} - \mathrm{T}_0) + \tfrac{1}{2}(\mathrm{d}\omega/\mathrm{dt})(\mathrm{t} - \mathrm{T}_0)^2 + \ (\mathrm{t} - \mathrm{T}_0),$$

where is the estimated error in spin rate ω_0 at epoch T_0, and any non-zero spin rate at T_0 introduces error.

Second, adding a YORP parameter in shape inversion models and iteratively updating phase offsets between synthetic and observed lightcurves until ^{2} values show no significant difference. The YORP parameter corresponding to minimum ^{2} gives the YORP rotational acceleration [**?**].

Using asteroid (1620) Geographos as an example, we selected 74 lightcurves with large amplitudes and phase angles from 118 lightcurves between 1969–2019 [**?**, **?**] to solve Geographos's shape model. Figure 2 [Figure 2: see original paper] shows three views of Geographos's shape model. The spin axis coordinates are (52.2 ± 6°, -40.0 ± 7°) and the rotational period is P = 5.223319 ± 0.000002 h (T_0 = 2440229.0).

Least-squares fitting of phase differences between 74 observed lightcurves and best constant-period synthetic lightcurves yields a YORP rotational acceleration of $= 1.195 \times 10^{-8}$ rad/d^2 (see Figure 3 [Figure 3: see original paper]). Ďurech et al. generated synthetic lightcurves for both constant-period and YORP-parameter-added cases. Figure 4 [Figure 4: see original paper] compares synthetic and observed lightcurves: dashed lines show constant-period synthetic curves with obvious phase differences from observations; solid lines show synthetic curves with YORP parameter $= 1.15 \times 10^{-8}$ rad/d^2 that fit observations well [**?**]. Asteroid brightness depends on viewing angle , solar azimuth $_0$, and phase angle α. The first phase-offset fitting method is time-consuming and introduces errors; the second method is more efficient.

To date, YORP-driven rotational accelerations have been directly detected in only six near-Earth asteroids (see Table 2), all in spin-up states; no YORP-decelerated asteroids have been found.

Table 2 Six asteroids with directly detected YORP spin rate changes

Asteroid	Semi-major axis (AU)	Absolute magnitude (mag)	Mean diameter (km)	Geometric albedo	Rotational period (h)	YORP accel. (rad/d^2)	Timescale (Myr)	Lightcurve span
(54509) YORP	0.560	0.345	0.230	0.336	5.223336 ± 2\$×10^{-6}\$	(1.15 ± 0.15)\$×10^{-8}\$	6.9 ± 0.9	1969–2008
(1620) Geographos	1.45 ± 0.22	1.80 ± 0.30	0.327 ± 0.001	0.113 ± 0.002	5.223319 ± 2\$×10^{-6}\$	(1.1 ± 0.5)\$×10^{-8}\$	5.2 ± 2.2	1980–2007
(25143) Itokawa	0.265 ± 0.0375	0.25 ± 0.08	0.38 ± 0.13	0.345 ± 0.002	0.20289941 ± 10^{-8}	(3.5 ± 0.3)\$×10^{-6}\$	0.58 ± 0.06	1987–2012
(1862) Apollo	0.115 ± 0.004	0.044 ± 0.002	3.065448 ± 3\$×10^{-6}\$	(5.3 ± 1.3)\$×10^{-8}\$	2.5 ± 0.5	2000–2007	[61,62]	
(3103) Eger	0.1783583 ± 7\$×10^{-7}\$	0.2176 ± 0.0006	0.6658 ± 0.0001	0.06248 ± 0.00005	0.1701 ± 0.0005	0.0829783 ± 3\$×10^{-7}\$	0.07429 ± 0.00007	7.042027 ± 5\$×10^{-6}\$
(101955) Bennu	0.204	0.8 × 10^{-8}	1999–2018	[5],[66]				

Additionally, YORP effects have been confirmed in (1865) Cerberus [?] and (2100) Ra-Shalom [?, ?], but only estimated ranges for YORP rotational acceleration have been provided. Although (161989) Cacus was clearly detected with YORP effects [?, ?] and a rotational acceleration of 1.9\$×10^{-8}\$ rad/d^2 was given, the result relies too heavily on 1978 photometric data, yielding low confidence, so we exclude it from the measured list.

Direct YORP detection requires both dense lightcurve data for shape inversion and long temporal baselines, limiting the number of detections. Table 3 lists asteroids with future observational potential for YORP rotational change measurements—these are priority targets.

Table 3 Fifteen asteroids potentially measurable for YORP rotational changes in future observations

Asteroid	Semi-major axis (AU)	Absolute magnitude (mag)	YORP accel. (rad/d^2)
(1685) Toro	1.368	14.23	$\sim 2.3 \times 10^{-9}$
(162173) Ryugu	1.190	19.30	$\sim 1.9 \times 10^{-8}$
(161989) Cacus	1.123	16.05	$(-5.98\text{–}2.03) \times 10^{-8}$
(2100) Ra-Shalom	0.832	16.84	6.0×10^{-8}
(1865) Cerberus	1.080	11.46	0.8×10^{-8}
2007 DD	1.233	10.197	82 ± 0.00003
(951) Gaspra	2.386	7.6312 ± 0.0002	3.755067 ± 0.000002
1996 HW1	1.110	19.8200 ± 0.0003	6.803286 ± 0.000005

Shape inversion models based on lightcurves are the primary method for detecting YORP rotational acceleration and have proven reliable [?]. However, these models are insensitive to surface microstructure, limiting YORP calculation precision, making integration with thermophysical models essential.

3.2 Thermophysical Models

Early thermophysical models for different targets included STM (Standard Thermal Model), FRM (Fast Rotating Model), and NEATM (Near-Earth Asteroids Thermal Model), all simplified thermal models treating asteroids as non-rotating spheres. To better describe surface temperature distributions, advanced Thermophysical Models (TPM) and Advanced Thermophysical Models (ATPM) were developed. TPM constrains asteroid albedo, specific heat capacity, and density through infrared observations. However, TPM assumes triaxial ellipsoid shapes, limiting YORP calculations. In 2011, Rozitis et al. [?] proposed the Advanced Thermophysical Model.

Figure 5 [Figure 5: see original paper] shows main types of thermal radiation from asteroid surfaces. Thermophysical models typically neglect multiple radiation effects when calculating YORP effects.

In 2014, Lowry et al. [?] applied advanced thermophysical models to calculate Itokawa's YORP rotational acceleration, finding significant deviations from shape inversion model results (see Figure 6 [Figure 6: see original paper]).

Advanced thermophysical models did not consider thermal-infrared beaming or global self-heating effects. However, thermophysical models can constrain physical parameters like density and albedo when YORP-driven rotational acceleration is known. In 2018, Jiang and Ji [?] detailed progress in asteroid thermophysical models for YORP research.

In 2015, Ševeček et al. [?] presented an advanced thermophysical model accounting for shadowing from boulder structures and local self-heating effects, with facet recoil force:

$$\mathrm{d}\mathbf{F} = \text{-}\ (\ \sigma \mathrm{u}^4/\mathrm{c})\ \mathbf{n} + (\cos\,\alpha\ /\ \pi)\ \ \_\Gamma\ (|\mathbf{r}\ \text{-}\ \mathbf{r'}|)^{-2}\ (|\mathbf{r}\ \text{-}\ \mathbf{r'}|)\ \mathrm{d}\Gamma',$$

where **r** and **r'** are position vectors of surface points, σ is the Stefan-Boltzmann constant, c is light speed,   is thermal emissivity, u is temperature, **n** is the outward normal vector, α is the angle between facet normal and position vector **r**, Γ_1 represents asteroid surface boundaries, and Γ denotes surface facets. This model still neglects thermal-infrared beaming and global self-heating effects, requiring further refinement for YORP calculations.

4.1 Distribution of Asteroid Spin Rates

YORP effects influence main-belt and near-Earth asteroids differently. In 2008, Pravec et al. [?] plotted spin rate distributions for 268 main-belt and Mars-crossing (MB/MC) asteroids with diameters 3–15 km (see Figure 7 [Figure 7: see original paper]). MB/MC asteroid spin rate distributions are relatively flat, with higher proportions of slow rotators. Near-Earth asteroids show clear bimodal spin rate distributions (see Figure 8 [Figure 8: see original paper]).

In 2009, Rossi et al. [?] simulated near-Earth asteroid spin distributions, finding obvious deviations from observations when YORP effects were excluded, but good agreement when included. This demonstrates YORP's significant influence on asteroid spin evolution.

Figure 9 [Figure 9: see original paper] shows latitude-longitude distributions for asteroids smaller than 30 km. The latitude distribution shows clear bimodal characteristics, while longitude shows no distinct features. To further characterize spin axis orientation distributions, Hanuš et al. [?] created an asteroid spin evolution model including YORP effects, collisions, and other factors. Simulations matched observations, showing bimodal features (see Figure 10 [Figure 10: see original paper]).

Alignment of asteroid spin axes provides strong evidence for YORP-driven evolution, particularly evident in asteroid families through alignment of family members' spin axes (Slivan states). In 2002, Slivan et al. [?] discovered aligned spin axes among nine members of the Koronis family; Vokrouhlický et al. [?] subsequently linked this alignment to YORP effects on family members.

In 2015, Vraštil et al. [?] simulated inner main-belt asteroid evolution, suggesting the Massalia family may also be in a Slivan state. In 2016, Vraštil et al. [?]

numerically explored parameter space for Slivan states in the main belt, finding that low-inclination outer main-belt asteroids likely occupy Slivan states, though not yet observationally confirmed. In reality, YORP effects are less significant for outer main-belt asteroids, with spin-orbit resonance being the main reason for Slivan state existence.

In 2016, Paolicchi et al. [?] identified a cavity region in plots of family members' absolute magnitude versus semi-major axis, termed the "YORP-eye." The YORP-eye size correlates with family age; younger families lack this structure [?]. Older families have smaller magnitude values corresponding to the YORP-eye, providing an independent method for estimating family ages [?]. In 2019, Marzari et al. [?] constructed an asteroid family evolution model incorporating Yarkovsky/YORP effects and collisions, successfully reproducing V-shaped diagrams and demonstrating that YORP-eyes result from Yarkovsky/YORP-driven evolution.

4.3 Parameterized YORP Calculation Method

Parameterized YORP calculation methods replace shape and thermal inertia effects with YORP coefficients based on real asteroid physical and orbital parameters.

In 2009, Rossi et al. [?] provided the formula for YORP effects on asteroid spin rates:

$d\omega/dt = (G_1 / (a^2 \surd(1 - e^2) \quad D^2))$ C_Y,

where G_1 is the modified solar constant (~6.4×10^{10} $kg \cdot km \cdot s^{-2}$), a, e, , D are orbital semi-major axis, eccentricity, bulk density, and effective diameter, and C_Y is the YORP coefficient (or YORP factor).

In 2013, Rozitis et al. [?] gave YORP rotational acceleration detection conditions:

$|d\omega/dt| > 8\pi$ X C_P / T_{CAM}^{2},

where C_P is the rotation precision coefficient, T_{CAM} is the photometric data time span, and X is the confidence level for YORP detection. YORP detection conditions are independent of rotation period. This parameterized method can estimate YORP magnitude, calculate detection probability given a lightcurve time span, or determine required time span given a detection probability. It is unsuitable for fast rotators (period $<$ 2.2 h) or slow rotators (period $>$ 20 h), and has large errors for individual samples but is statistically significant.

5.1 Selection of Observable YORP Effect Targets

The proliferation of dense and sparse asteroid photometric data enables development of universal selection models for YORP effect candidates, greatly improving detection efficiency. Targeting asteroids where YORP rotational acceleration likely exists and is detectable, we establish a YORP candidate selection model based on lightcurve requirements for shape inversion.

However, establishing a complete selection model faces uncertainties. First, YORP torque is closely related to asteroid diameter, density, thermal inertia, and other physical parameters, which vary significantly between asteroids and lack unified reference standards. Second, whether sparse photometric data truly aid YORP detection remains unclear [?], raising questions about whether selection models should consider asteroids with abundant sparse data. Additionally, whether asteroids in resonance regions should be candidate targets requires consideration.

5.2 Influence of Microstructure on YORP Calculations

Lightcurve-based shape inversion models lack capability to resolve surface microstructure (e.g., protruding boulders, impact craters). In 2009, Statler et al. [?] first noted YORP effects are extremely sensitive to surface microstructure, even capable of reversing YORP torque direction, making quantification of microstructure effects important. In 2008, Ďurech et al. [?] estimated microstructure effects on Apollo asteroids at ~10% of their YORP effect; comparative studies of rough versus smooth models found microstructure effects on Geographos within 5% [?]. Only in 2015 did Golubov et al. [?] attempt mathematical quantification of microstructure effects on real asteroids.

5.3 Thermal-Infrared Beaming and Global Self-Heating Effects

Asteroid rough surfaces, large craters, and boulder shadows produce two effects: thermal-infrared beaming [?] and global self-heating [?]. Figures 11 [Figure 11: see original paper] and 12 [Figure 12: see original paper] illustrate these effects.

Thermal-infrared beaming refers to observed infrared radiation increases at certain phase angles. Without considering surface roughness, radiation direction is typically normal to the surface. In 2011, Rozitis et al. [?] proposed thermophysical models must include thermal-infrared beaming. In 2012, Rozitis et al. [?] found beaming magnitude is independent of thermal inertia and albedo but highly sensitive to surface roughness, with YORP suppression increasing with roughness. Compared to smooth surfaces, thermal-infrared beaming can reduce YORP effects by up to half. Neglecting beaming in thermophysical models may yield large errors or inaccurate YORP rotational accelerations.

Local self-heating occurs when unilluminated concave surfaces receive reflected light from other facets, heating shadowed regions that then emit thermal radiation; global self-heating occurs across the entire asteroid. Global self-heating must be considered for asteroids like Itokawa with large shadowed regions. In 2013, Rozitis et al. [?] noted global self-heating reduces YORP sensitivity to surface microstructure. Similar to rough-surface thermal-infrared beaming, global self-heating suppresses YORP effects by ~10%.

Considering both effects separately at higher precision is necessary, though real asteroids typically exhibit both simultaneously. Their combined influence on YORP effects represents a future research direction.

6 Summary and Outlook

This paper reviews observational research progress on asteroid YORP effects, covering theoretical foundations, direct detection, and statistical analysis. Shape inversion models from lightcurve data and thermophysical models are effective tools for detecting YORP rotational acceleration. Shape inversion requires long time-span dense photometric data, severely limiting YORP measurements, resulting in only six near-Earth asteroids with directly measured YORP accelerations. Thermophysical models, lacking thermal-infrared beaming and global self-heating effects, reduce YORP detection precision but effectively constrain thermal inertia and other parameters when YORP acceleration is known. Due to limited shape data and thermophysical models, we also introduce a parameterized method using YORP coefficients to represent shape and thermal inertia effects, facilitating statistical studies and estimating detection probabilities given observation time spans.

Key challenges for asteroid YORP research include quantifying surface microstructure and advancing thermophysical models. Photometric data will remain the primary YORP detection method. With increasing asteroid lightcurve data, effective candidate selection models become necessary to find asteroids undergoing YORP-driven spin-down. Additionally, self-limiting and self-enhancing YORP processes represent important future research for complete YORP theory [?]. Thus, many meaningful investigations remain for scholars to explore as YORP research continues to develop.

References

[1] Pravec P, Harris A W. Icarus, 2000, 148: 12
[2] Scheeres D J, Marzari F, et al. Icarus, 2011, 214: 622
[3] Jacobson S A, Francesco M, et al. MNRAS, 2014, 439: 95
[4] Lowry S C, Weissman P R, et al. A&A, 2014, 562: A48
[5] Hergenrother C W, Maleszewski C K, et al. Nature Communications, 2019, 10: 1291
[6] Vokrouhlický D, Chesley S R, et al. Icarus, 2015, 252: 277
[7] Scheeres D J, et al. Icarus, 2018, 304: 183
[8] Kevin J G, David A M, et al. Icarus, 2018, 304: 162
[9] Cheng B, Yu Y, et al. Nature Astronomy, 2020, 5: 134
[10] Michel P, Ballouz R L, et al. Nature Communications, 2020, 11: 2655
[11] Kleyna J T, Meech K J, et al. ApJ, 2019, 874: L20
[12] Lauretta D S, Hergenrother C W, et al. Science, 2019, 366: 3544
[13] Veras D, Scheeres D J, et al. MNRAS, 2020, 492: 2437

[14] Veras D, Pier-Emmanuel Tremblay, et al. MNRAS, 2020, 765: 775
[15] Veras D, Kevin Heng, et al. MNRAS, 2020, 496: 2292
[16] Yarkovsky I O. The density of luminiferous ether and the resistance it offers to motion. Brož M, Vokrouhlický D. Charles: Charles University, 2006: 153
[17] Radzievskii V V. Doklady Akademii Nauk SSSR, 1954, 97: 49
[18] Paddack S J. Journal of Geophysical Research, 1969, 74: 4379
[19] Rubincam D P, et al. Icarus, 2000, 148: 2
[20] Lowry S C, Alan Fitzsimmons, et al. Science, 2007, 316: 272
[21] Rubincam, Paddack, et al. Icarus, 2010, 209: 863
[22] Yan X R, Li J F. SCIENTIA SINICA Physica, Mechanica& Astroomica, 2019, 49: 8
[23] Vokrouhlický D, Čapek D, et al. Icarus, 2002, 159: 449
[24] Harris A W. Bulletin of the American Astronomical Society, 2004, 36: 1185
[25] Breiter S, Vokrouhlický D, et al. MNRAS, 2011, 410: 2807
[26] 李俊峰, 曾祥远, 张韵. 力学与实践, 2016, 38: 603
[27] Nesvorný D, Vokrouhlický D, et al. AJ, 2007, 134: 1750
[28] Vokrouhlický D, Čapek D, et al. Icarus, 2004, 172: 526
[29] William B F, Vokrouhlický, et al. Annual Review of Earth and Planetary Sciences, 2006, 34: 157
[30] Binzel R P. Nature, 2003, 425: 131
[31] Brož M, Vokrouhlický D, et al. Proceedings IAU Symposium, 2005, 1: 351
[32] Hanuš J, Ďurech J, et al. A&A, 2011, 530: 16
[33] Warner B D, Harris A W, et al. Icarus, 2008, 197: 497
[34] Pravec P, Harris A W, Vokrouhlický D, et al. Icarus, 2008, 179: 479
[35] Rubincam D P, Paddack S J, et al. Icarus, 2010, 209: 863
[36] Vokrouhlický D, Brož M, et al. Dynamics of Populations of Planetary Systems, 2005, 197: 145
[37] Nesvorný D, Bottke W F, et al. ApJ, 2003, 591: 486
[38] Vokrouhlický D, Brož M, et al. Proceedings of the International Astronomical Union, Cambridge University: IAUC, 2004: 145
[39] Ćuk M, Burns J A, et al. Icarus, 2005, 176: 418
[40] McMahon J, Scheeres D J, et al. Asteron, 2010, 106: 261
[41] McMahon J, Scheeres D J, et al. Icarus, 2010, 209: 494
[42] Pravec P. http://www.asu.cas.cz/~asteroid/binastdata.htm, 2019
[43] Taylor P A, Margot J L, et al. Icarus, 2014, 229: 418
[44] Ćuk M, Burns J A, et al. American Astronomical Society, 2005, 36: 1184
[45] Jacobson S A, Scheeres D J, et al. ApJ, 2014, 780: 21
[46] Jacobson S A, Scheeres D J, et al. ApJL, 2011, 736: 5
[47] Steinberg E, Re'em Sari, et al. AJ, 2011, 141: 10
[48] Rubincam D P, et al. Icarus, 2007, 192: 460
[49] Golubov O, Krugly Y N, et al. The Astronomical Society, 2012, 752: 5
[50] Golubov O, Scheeres D J, Krugly Y N. ApJ, 2014, 794: 9
[51] Ďurech J, Sidrin V, et al. https://astro.troja.mff.cuni.cz/projects/damit, 2019

[52] Ďurech J, Sidorin V, Kaasalainen M, et al. A&A, 2010, 513: 13
[53] Ďurech J, Benoit C, Marco D. ASTEROIDS IV: The Yarkovsky and YORP Effects, Tucson: University of Arizona Press, 2015: 183
[54] Lowry S C, Weissman P R, Duddy S R. A&A, 2014, 562: 9
[55] Harris A W, Young J W, et al. Icarus, 1989, 81: 314
[56] 李彬, 赵海斌. 硕士论文, 南京: 中国科学院紫金山天文台, 2012: 10
[57] Kaasalainen M, Torppa J, et al. Icarus, 2001, 153: 24
[58] Kaasalainen M, Torppa J, et al. Icarus, 2001, 153: 37
[59] Ďurech J, Vokrouhlický D, et al. A&A, 2008, 489: 25
[60] Brian D W. http://alcdef.org/PHP/alcdef-GenerateALCDEFPage.php, 2019
[61] Mikko Kaasalainen, Ďurech J, et al. Nature, 2007, 446: 420
[62] Ďurech J, Vokrouhlický D, et al. A&A, 2008, 488: 345
[63] Ďurech J, Vokrouhlický D, Pravec P. A&A, 2017, 609: 10
[64] Ďurech J, Vokrouhlický D, et al. A&A, 2012, 547: 9
[65] Taylor P A, Jeau-Luc Margot, et al. Science, 2007, 316: 274
[66] William F B, Vokrouhlický D, et al. Icarus, 2014, 247: 191
[67] Rozitis B, Green S F, et al. MNRAS, 2013, 430: 1376
[68] Ďurech J, Vokrouhlichký D, Pravec P. American Astronomical Society, DPS meeting 48, 2016, 504: 02
[69] William B, Vokrouhlický D, et al. AAS/Division of Dynamical Astronomy Meeting, 2019, 51: 200
[70] Müller T G, Ďurech J, et al. A&A, 2017, 599: 103
[71] Hanuš J, Ďurech J, et al. Icarus, 2015, 256: 101
[72] Kwiatkowski T. A&A, 2010, 509: 7
[73] Kwiatkowski T. A&A, 2010, 509: 11
[74] Rubincam D P, Rowlands D, et al. Journal of Geophysical Research, 2002, 107: 5065
[75] Hanuš J, Brož M, et al. A&A, 2013, 559: 19
[76] Rożek A, Lowry S, eds. Asteroids, Comets, Meteors 2014. Helsinki: University of Helsinki, 2014: 449
[77] Hanuš J, Ďurech J, et al. A&A, 2016, 586: 24
[78] Kaasalainen M, Ďurech J, et al. arXiv:2005.09947, 2020
[79] Rozitis B, Green S F, et al. MNRAS, 2011, 415: 2042
[80] 姜浩轩, 季江徽. 天文学进展, 2018, 36: 3
[81] Ševeček P, Broz M, Čapek D, et al. MNRAS, 2015, 450: 2104
[82] Rossi A, Marzari F, Scheeres D J. Icarus, 2009, 202: 95
[83] Slivan, Stephen M, et al. Nature, 2002, 419: 49
[84] Vokrouhlický D, et al. Nature, 2003, 424: 147
[85] Vraštil J, Vokrouhlický D, et al. A&A, 2015, 579: 10
[86] Vraštil J, Vokrouhlický D, et al. A&A, 2016, 579: 6
[87] Paolicchi P, Zoran Knežević, et al. Icarus, 2016, 274: 314
[88] Rosaev A E, Plávalová E. Icarus, 2018, 304: 135
[89] Hanuš J, Delbo, et al. Icarus, 2018, 299: 84
[90] Marzari F, Rossi A, Paolicchi P, et al. EPSC-DPS Joint Meeting 2019, 2019: EPSC-DPS2019-264

[91] Hanuš J, Ďurech J, et al. A&A, 2013, 551: 11
[92] Statler T S, et al. Icarus, 2009, 202: 502
[93] Golubov O A, Pyrohova U V, et al. Astronomical School's Report, 2015, 11: 135
[94] Rozitis B, Green S F, et al. MNRAS, 2012, 423: 367
[95] Rozitis B, Green S F, et al. MNRAS, 2013, 433: 603
[96] Statler T, Cotto-Figueroa D, et al. ApJ, 2015, 803: 18

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.