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Postprint: Research Advances on the Physical Properties of Active Asteroid (3200)Phaethon

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Abstract

We comprehensively review the perihelion observational data and near-Earth observation events of active asteroid (3200) Phaethon, analyzing the activity mechanisms near perihelion, particularly those driven by thermal fracturing, water ice sublimation, and Na sublimation. Based on investigations of Phaethon' s spectral data, albedo, and polarization, we summarize research findings regarding its surface physical properties and composition, providing abundant evidence for a comprehensive understanding of this celestial body. We conduct an in-depth exploration of the Phaethon-Geminid meteoroid stream complex, the classification of active asteroids, and their origin tracing. In studies of asteroid orbital evolution and thermal-physical modeling, we utilize the MERCURY6 integrator to perform millennial-scale inversion of Phaethon' s orbital elements, preliminarily obtaining motion patterns such as its perihelion distance; and based on the Advanced Thermophysical Model (ATPM), we integrate and fit multi-band infrared observational data to derive Phaethon' s thermal inertia, albedo, and diameter. Finally, focusing on space exploration of active asteroids, we prospect the JAXA space mission DESTINY+ and China' s Tianwen-2 exploration plan.

Full Text

Preamble

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Research Progress on Physical Properties of Active Asteroid (3200) Phaethon

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Abstract

This paper provides a comprehensive review of perihelion observations and significant observational events such as ground-based observations of the active asteroid (3200) Phaethon during its close approach to Earth. It summarizes the current research priorities of (3200) Phaethon, followed by an investigation into the mechanisms governing its perihelion activity, in which the highly discussed thermal fracturing and the theory of water ice and Na sublimation driving theory are elaborated in detail. Detailed analyses of spectroscopic signatures, albedo variations, and polarization measurements are presented to elucidate surface composition and physical characteristics, thereby providing substantial evidence for understanding the asteroid’ s surface properties. Phaethon-Geminid Complex (PGC) relation discussions and studies such as the classification of active asteroids and the traceability of Phaethon are further summarized. In the study of asteroid dynamical evolution and thermal physics models, the MERCURY6 integrator was employed on the orbital elements of Phaethon on a millennial timescale to derive the results on the asteroid’ s perihelion distance and other orbital characteristics. Additionally, the advanced thermophysical model (ATPM) was applied to fit a compilation of infrared multi-band observational data, yielding estimates for thermal inertia, albedo, and diameter. Finally, JAXA space mission DESTINY+ and China’ s upcoming Tianwen-2 mission are discussed.

Keywords: asteroid; mechanism of activity; near-earth asteroid

1. Introduction

The Geminid meteor shower in mid-December each year is one of the most intense and regular annual meteor showers. In 1983, the Infrared Astronomical Satellite (IRAS) discovered its parent body to be asteroid (3200) Phaethon (hereinafter referred to as Phaethon) during a sky survey near the orbit of the Geminid meteoroid stream, and it was temporarily designated 1983 TB at that time. Currently, Phaethon is considered an active near-Earth asteroid that likely originated in the main belt, representing a key celestial body intermediate between comets and asteroids, also known as an active asteroid. Multi-color photometric measurements reveal that Phaethon exhibits a blue spectral surface, in stark contrast to the red spectra typical of cometary nuclei.

According to observations from the Arecibo Observatory, Phaethon is a top-shaped asteroid with an effective diameter of 5.7 km and a rotation period of approximately 3.6 h. In 2021, more precise size measurements were obtained through occultation observations, indicating an equatorial diameter of 6.13 ± 0.05 km and a polar diameter of 4.40 ± 0.06 km, revealing a more flattened ellipsoidal shape than previously thought, particularly at the polar regions. [Figure 1: see original paper] shows Phaethon' s shape model from four different viewing perspectives.

Phaethon possesses a highly elliptical orbit with semi-major axis a = 1.271 AU, eccentricity e = 0.890, inclination i = 22.3°, and orbital period of 523.5 d; its perihelion distance q = 0.14 AU and aphelion distance Q = 2.40 AU, placing it interior to Jupiter' s orbit at 5.2 AU. Two other asteroids, (155140) 2005 UD and (225416) 1999 YC, have orbital elements and spectra similar to Phaethon, and together with the Geminid meteor stream they are collectively referred to as the Phaethon-Geminid Complex (PGC).

Initially, Phaethon was thought to be inactive. However, in 2009, the Heliospheric Imager (HI-1) on the Solar Terrestrial Relations Observatory-A (STEREO-A) first reported a brightening phenomenon near perihelion, which peaked a few hours after perihelion and faded within two days. Similar anomalous brightening and anti-solar dust tail features were observed during the 2012 and 2016 perihelion passages, demonstrating that this activity recurs periodically.

In terms of asteroid classification, Phaethon was previously categorized as an F-type asteroid within the C-complex, later merged into the B-type classification. The Japan Aerospace Exploration Agency (JAXA), in collaboration with the Planetary Exploration Research Center at Chiba Institute of Technology, is planning the DESTINY+ (Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science) mission to investigate Phaethon. Originally scheduled for launch in 2024, the mission has been postponed to 2028, with a planned flyby of Phaethon. China is also preparing to deploy missions to active asteroids, with the Tianwen-2 probe scheduled for launch in 2025 targeting active asteroid 311P, aiming to lay groundwork for subsequent Jupiter and asteroid exploration missions.

Section 2 introduces important observational events of Phaethon; Section 3 focuses on discussing activity mechanisms near perihelion; Section 4 presents analysis of observational results; Section 5 covers related modeling studies such as orbital evolution and thermophysical models; Section 6 discusses relationships with other asteroids and population studies; Section 7 introduces future mission plans; and finally, the paper concludes with a summary and outlook on directions worthy of further exploration.

2.1 Perihelion Activity Observations

Direct observations near perihelion are challenging because Phaethon' s perihelion distance is close to the Sun, resulting in solar elongation angles smaller than 8°. Jewitt and Li utilized the HI-1 camera on STEREO-A to first observe Phaethon' s activity, revealing a brightening of approximately 2 mag after perihelion (June 20.2 ± 0.2, 2009 UT), peaking a few hours later and fading within two days. After excluding geometric effects and plasma impact excitation, the brightening was interpreted as resulting from dust ejection, with the total ejected dust mass estimated at 2.5×10^8 kg for millimeter-sized particles.

Subsequently, Li and Jewitt discovered comet-like tail structures in optical imaging near perihelion. In 2009 and 2012, astronomers observed the tail growing to its full length (approximately 2.5×10^5 km) within one day, indicating dust ejection accelerations of at least 0.07 m s^{-2}, consistent with radiation pressure acting on spherical dust grains about 1 m in size. This yielded a total ejected dust mass estimate of approximately 3×10^5 kg. Analysis of observations from 2009, 2010, and 2012 confirmed that this brightening recurs periodically, with tail structures appearing only during the two-day brightening period.

On August 19.82, 2016, Phaethon again brightened by 2 mag shortly after perihelion passage, forming a tail structure 0.1° long the following day. This elongated structure quickly disappeared, essentially identical to previous tail features. Based on the Schleicher-Marcus phase function, micrometer-sized dust would be enhanced by forward scattering effects at phase angles up to 166°. Attributing the brightening to this mechanism—where Phaethon brightens due to forward-scattering phase angles and subsequently dims as the phase angle decreases—yields dust sizes of 0.5 m and total mass loss of 10^4–10^5 kg. However, calculations of effective scattering cross-sections from large-phase-angle detection data by STEREO' s COR2 coronagraph field of view place a 3σ upper limit of 300 kg on dust mass ejected during perihelion, far below the 3×10^5 kg total mass derived from HI-1 observations. Therefore, additional evidence is needed to confirm the correlation with micrometer-sized dust particle ejection.

Considering the wavelength differences compared to COR2 observations, HI-1 has transmission near 400 nm and 1000 nm, and its filter bandpass was found to have non-negligible transmission at the Na I D line. Consequently, Phaethon' s brightening has been hypothesized to result from Fe I emission lines near 400 nm or Na I D emission lines at 589.0/589.6 nm. In May 2022, the Large Angle Spectrometric Coronagraph (LASCO) on the Solar and Heliospheric Observatory (SOHO) and the HI-1 imager on STEREO-A captured Na I D line emission from Phaethon, with observations through an orange filter showing significantly brighter activity than through a blue filter that does not transmit Na I D lines. Using SOHO LASCO, observers detected resonance fluorescence at 589.0/589.6 nm in Phaethon' s tail, demonstrating that its brightening and tail development result from Na release. This observation strongly supports the Na-driven brightening theory for Phaethon, with detailed analysis provided in Section 3.

On December 16, 2017, Phaethon passed Earth at a distance of 0.069 AU, the closest approach since 1974 until 2093. Numerous ground-based telescopic observations were conducted to search for small fragments and dust particles at high resolution, investigating whether Phaethon' s activity persists beyond perihelion. However, no activity or debris was detected, further supporting the conclusion that the Geminid meteor shower does not result from steady-state activity.

To date, Phaethon has exhibited only weak activity near perihelion. Ye et al. conducted searches for gas and dust emissions and fragments from December 14–18, 2017, finding no fragments 15-100 m in its vicinity. Spectral comparisons with comet C/2017 O1 (ASASSN) confirmed the absence of cometary emission lines. These observations established a 3σ upper limit on dust production rates of 0.007–0.2 kg s^{-1}. Additionally, Very Large Telescope observations at 10.7 m revealed no dust emission or fragments. Ground-based observations from the Canada-France-Hawaii Telescope (CFHT) and the Xingming Observatory in Xinjiang, China, also found no cometary activity or meter-sized fragments, estimating mass loss upper limits of 0.06 ± 0.02 kg s^{-1} at 1.449 AU from the Sun and 0.2 ± 0.1 kg s^{-1} at 1.067 AU. This activity intensity is insufficient to supply the Geminid meteor stream.

The geometric relationship between Phaethon, the Sun, and Earth's orbit makes direct acquisition of absolute magnitude at zero phase angle difficult, complicating diameter calculations using absolute magnitude and albedo derived from infrared observations. The 2017 close approach provided an opportunity for radar-based precise size determination. [Figure 2: see original paper] shows rotation images from Arecibo Observatory observations, based on which Phaethon' s equivalent diameter was estimated at 5.7 km, larger than previous thermophysical model estimates (5.1 ± 0.2 km). The observations revealed a likely oblate spheroid shape with kilometer-scale large depressions in equatorial and low-latitude regions and a prominent radar-dark feature near one pole, interpreted as a possible impact crater.

Ground-based observations obtained clearer light curves, colors, and polarization data for Phaethon. Tabeshian et al. presented light curves for phase angles of 20°–100° (shown in [Figure 3: see original paper]), deriving mean colors of B–V = 0.702 ± 0.004 mag, V–R = 0.309 ± 0.003 mag, and R–I = 0.266 ± 0.004 mag. The B–V color varies with observational latitude, and photometric variations are consistent with depressions reported by Arecibo, suggesting large craters on Phaethon' s surface that may be related to the Geminid meteor stream.

Occultation methods can also determine asteroid sizes with high precision by directly measuring the shadow cast on Earth' s surface when an asteroid occults a background star, with precision determined by timing accuracy. To obtain more precise dimensions, DESTINY+ science team members utilized occultation observations to estimate Phaethon' s diameter, with 18 stations detecting stellar occultation phenomena. On October 3, 2021, astronomers in western Japan observed Phaethon occulting a 12 mag star in Auriga. The occultation cross-section could be approximated by an ellipse with major and minor diameters of 6.12 ± 0.07 km and 4.14 ± 0.07 km, respectively, at a position angle of 117.4° ± 1.5°. Observations from October 13, 2021, yielded major and minor diameters of 6.13 ± 0.05 km and 4.40 ± 0.06 km. The DESTINY+ science team will revise Phaethon' s three-dimensional shape model based on these occultation results to more accurately develop the spacecraft.

From October 31 to November 11, 2018, the Wide-field Imager for Solar Probe (WISPR) on the Parker Solar Probe (PSP) mission encountered dust in Phaethon’ s orbit within 0.0277 AU, with observed dust trails shown in [Figure 4: see original paper]. The most prominent dust trails were concentrated near perihelion, with distributions highly coincident with Phaethon’ s orbit but offset beyond perihelion. In 2022, Battams et al. summarized and analyzed dust observations from nine independent flybys between October 2018 and August 2021, finding that dust trails do not perfectly follow Phaethon’ s orbit, with discrepancies increasing with true anomaly. If Phaethon’ s orbital elements are modified by reducing its argument of perihelion by exactly 1.0°, its orbit nearly matches the observed dust trails.

On May 2, 2021 (E8), WISPR-I and WISPR-O on PSP recorded observations. The estimated dust mass ranges from 10^{10} to 10^{12} kg, far exceeding the amount of dust ejected by Phaethon at its current activity level and comparable to the total mass of the Geminid meteor stream. The observed dust trail brightness is relatively uniform, with no clear relationship between brightness and heliocentric distance, suggesting that dust has uniformly filled the orbit. Battams et al. proposed that this dust trail may be produced by a portion of Geminid meteoroids near Phaethon and may not share the same origin as meteoroids encountered by Earth. It remains unclear whether this dust trail results from massive dust ejection by Phaethon.

3. Asteroid Activity Mechanisms

Active asteroids exhibit various activity mechanisms, including radiation pressure, electrostatic repulsion, sublimation (e.g., 133P), thermal fracturing, rotational instability (e.g., 311P), and impacts. Current research suggests that Phaethon’ s primary activity mechanisms may involve water ice sublimation, thermal fracturing, and Na-driven processes, with additional consideration of rotational instability, radiation pressure on debris, and cohesive forces. These mechanisms can interact; for example, rotation can promote thermal fracturing.

3.1 Water Ice Sublimation

Most meteor stream parent comets experience mass loss through ice sublimation, where dust grains are exposed on the surface and dragged into space. Unlike comets, Phaethon’s activity is only observed near perihelion, with no dust or gas detected near or beyond Earth’s orbit. If sublimation drives its activity, volatiles must exist somewhere on Phaethon that can sublimate at high temperatures. Jewitt and Li argued that temperatures near perihelion reach approximately 1000 K, excluding the presence of surface water ice. While its spectrum shows no definitive features in the 3 m region, indicating no surface water ice or hydrates, internal water cannot be ruled out. If Phaethon originated in the outer solar system, water ice might be preserved internally, but whether it can drive current activity requires further investigation.

Assuming heat conducts to deep subsurface layers, Jewitt and Hsieh calculated a core temperature (Tc = 300 K) at which water ice cannot persist. Maclennan and Granvik conducted thermodynamic analysis using the orbTPM model based on the possibility of deeply buried water ice, estimating a sublimation timescale of 50 Myr for subsurface ice, while water ice within 200 m of the surface would completely sublimate within 5.5 Myr, leaving open the possibility of internal water ice.

Yu et al. proposed a dust-ice two-layer system to discuss whether internal water ice could survive long-term thermal evolution. Sublimation/condensation cycles in this system could produce transient gas bursts at perihelion, explaining observed dust tails. Calculations indicate that Phaethon would lose all buried ice on a timescale of 6 Myr, with dust outer layer thickness reaching hundreds of meters during evolution, providing the possibility of buried water ice today. Phaethon would have been more active in early stages when the dust outer layer was thinner.

3.2 Thermal Fracturing

Phaethon’ s dust tail appears only near perihelion, suggesting that brightening may result from pulsed release of dust grains increasing the effective cross-section and scattering more sunlight. Its high acceleration of 0.07 m s^{-2} is consistent with radiation pressure acting on 1 m-sized dust grains, indicating dust small enough to be strongly accelerated by radiation pressure.

Observations of the 2016 brightening event revealed a tail composed of dust particles with radii of approximately 0.5 m forming within one day after perihelion. Li and Jewitt argued that high temperatures near perihelion are more likely to cause thermal fracturing than ice sublimation. Thermal fracture and decomposition of mineral materials, such as desiccation shrinkage of hydrated silicates, represent processes that can both produce and eject dust from the surface. Dust is a product of thermal fracturing.

Four processes can eject dust in the thermal fracturing mechanism: (1) tension during thermal fracture can eject dust; (2) electrostatic forces can remove dust, with surface ions promoting dust adhesion and release; (3) solar wind radiation pressure can remove dust smaller than 1 mm at perihelion; and (4) rotation can clear surface dust during spin, with Phaethon’s rotation period of approximately 3.6 h and equatorial shape increasing the size limit for dust removal by radiation pressure. Phaethon’ s brightening and dust tail phenomena recur at perihelion due to rock thermal fracturing.

High-temperature dust production involves thermal fracturing caused by rock structural changes, loss of chemically bound water, uneven thermal expansion, and rapid heating. Phaethon’ s estimated perihelion temperature range of 743-1050 K reaches the minimum temperature required for decomposition of many rocks. Temperature increases gradually cause loss of chemically bound water and crystal structure changes, leading to rock contraction, insufficient internal stress, cracking, and dust production. However, gas drag from this process is insufficient to overcome gravity and eject material. Cyclic heating and cooling of rocks cause non-uniform thermal expansion, with local stresses exceeding material strength leading to crack initiation and propagation. Meteorite sample experiments show that crack growth and decomposition timescales are consistent with hypothesized regolith generation timescales, suggesting this process may be more effective than impacts at producing regolith. Rapid heating also causes insufficient thermal conduction in solids, leading to thermal expansion, with large temperature gradients acting locally on timescales shorter than thermal conduction timescales sufficient to trigger thermal fracture. Calculations using the rotation period yield a day-night temperature difference ΔT 500 K, with thermal gradient simulations indicating that thermal fracturing can eject particles up to 2 cm from Phaethon' s equatorial region. Even with slow temperature changes, shear stresses between rocks with different expansion properties can exceed structural strength, causing thermal fracturing.

The Geminid meteor stream mass is 10^{13}-10^{14} kg, with a loss rate of 320-3200 kg s^{-1} on millennial timescales. Simplified model calculations estimate brightening ejecta mass at 2.5×10^8 kg. Jewitt et al. re-estimated brightening mass loss at 3×10^5 kg for 1 m-sized dust, with a mass loss rate of approximately 0.1-3 kg s^{-1}. Hui and Li calculated dust ejecta mass for Phaethon' s 2016 activity event at 10^4-10^5 kg, with an average mass loss rate of 0.1-1 kg s^{-1}, consistent with previous results. This indicates that Phaethon does not provide steady replenishment for the Geminid meteor stream, leaving the meteoroid origin problem unresolved, though thermal fracturing cannot be ruled out as a source. Additionally, the phase lag of approximately 0.5 days between perihelion and anomalous brightening in 2009 and 2012 remains unclear in its relationship to thermal fracturing dust ejection.

3.3 Na-Driven Theory

Research on Phaethon indicates that temperatures on the sunward side exceed 1000 K, sufficient to vaporize rocks. Sublimation of rock components could also trigger activity by removing surface material to expose subsurface layers, enabling sustained activity and potentially catastrophic disruption. Na is a long-term volatile element in rock composition, and Na-driven activity may occur in water-poor bodies like Phaethon. Geminid meteorite meteoroids show Na depletion with low abundance, possibly due to Na depletion after dust ejection at high temperatures. Masiero et al. argued that Na sublimates from asteroid surfaces at high temperatures, causing dust ejection rather than depletion after ejection. To verify this, they simulated using the thermophysical model NIMBUS, finding that Na concentrations could locally form at least twice the original abundance, with impacts potentially triggering eruptions. Additionally, Na ionization and migration can promote dust particle adhesion and release on

Phaethon’ s surface.

Before discovering leakage in the HI-1 camera bandpass beyond 630–730 nm, Phaethon’ s brightening tail was not initially associated with Na sublimation, and the brightening could be explained by forward scattering enhancement of dust. Researchers argued that micrometer-sized dust requires one day to be accelerated by radiation pressure into a tail, making the tail appear elongated after perihelion. However, inferred micrometer-sized dust scattering from HI-1 data did not match dust mass from COR2 data, indicating that Phaethon’ s activity mechanism warrants further investigation. Considering previously excluded leakage components, the brightening could include Fe I emission lines near 400 nm or Na I D emission lines at 589.0/589.6 nm. Observations in May 2022 from SOHO LASCO and STEREO-A HI-1 suggest Na I D lines as the likely cause. Modeling emission line fluxes revealed that atomic production rates from gas sublimation peak one day after perihelion, with an asymmetric model better reproducing light curves similar to HI-1 observations. Simulations of brightening tail morphology support a gas sublimation-driven explanation.

Zhang et al. modeled the effects of radiation pressure, Doppler shift, and solar Fraunhofer lines on the Na I tail, with fluorescence efficiency variations and acceleration reproducing tail structure photometry and morphology from LASCO and HI-1 observations in 2022 and 17 earlier observations. The asymmetry before and after perihelion matches observations. The Na I tail model predicts physical tail elongation after perihelion due to the Greenstein effect. Near perihelion, when Phaethon’ s radial velocity $\dot{r} < 0$, surface Na atoms have similar velocities where radiation pressure decelerates, causing D lines emitted at velocities $\dot{r} \quad 0$ to coincide with solar spectrum Na I D absorption lines, reducing fluorescence excitation rates and suppressing Na atom acceleration and volatilization. At perihelion, Na atoms accelerate due to radiation pressure, rapidly producing a bright tail accelerating anti-sunward. Tail brightening at this time does not represent actual activity enhancement but reflects increased overall fluorescence efficiency of the Na I tail. Through MCMC modeling of the Na tail, researchers derived a Na I production of approximately $(1.09 \pm 0.15) \times 10^{29}$ atoms, with temperature dependence consistent with thermal desorption mechanisms, suggesting thermal desorption as the primary Na I production mechanism. This finding links Phaethon to sun-grazing comets observed by SOHO that produce Na emission.

3.4 Rotational Instability

Asteroid rotation rates can accelerate through external torques, chance impacts, gas release, and electromagnetic radiation to reach the limit where surface centripetal acceleration causes mass loss during rotation. Shorter rotation periods intensify thermal cycling, enhancing thermal fracture and driving rubble toward equatorial regions with lowest gravitational potential. For icy-free asteroids, radiation torque is the primary mechanism driving rotation to critical stability values.

The Yarkovsky effect, where thermal photon radiation exerts a net recoil thrust on asteroid surfaces, changes orbital semi-major axis through differential radiation pressure on the anti-solar side, significantly affecting meter- to kilometer-sized bodies, with Phaethon' s semi-major axis continuously decreasing under this influence. If the net force produces torque relative to the center of mass, this torque is called the YORP effect, which can change rotation magnitude and axis orientation, exciting precession or rapid rotation that alters morphology. The Geminid meteor stream is thought to form on millennial timescales, while YORP-driven evolution requires approximately 1 Myr, suggesting YORP-induced rotational mass ejection may be insufficient to form the meteor stream.

If Phaethon' s bulk density is 500–1500 kg m^{-3} (typical for B-type asteroids), its 3.6 h spin state may be near or above its critical rotation period. Combined with other activity mechanisms, this could cause large-scale deformation and trigger mass ejection. Indeed, its top shape and detected equatorial ridge morphology are consistent with expectations of surface material reshaping toward the equator driven by rotation. Rotation also enhances Phaethon' s structural disruption, while cohesive forces composed of van der Waals forces and structural friction can resist centrifugal forces from rotation and maintain shape.

Nakano and Hirabayashi developed a semi-analytical model to study rotation' s role in mass shedding mechanisms. They proposed that over its orbital lifetime (26 Myr), YORP effects cause Phaethon to spin up randomly, with an initial spin period shorter than the current period and greater structural deformation amplitude. Combined with other activity factors, this could lead to significant mass shedding events that produced the Geminid meteor stream, after which spin slowed to evolve into the current top shape. Further research is needed to address rotational reshaping processes and deformation mechanisms.

3.5 Other Brightening Causes

Besides activity, other causes could explain Phaethon' s brightening, including thermal radiation, solar wind effects, and phase angle scattering. Considering thermal radiation, with a perihelion distance of 0.14 AU, calculations for an isothermal spherical black body in equilibrium with sunlight yield a lower temperature limit of approximately 743 K and an upper limit of about 1050 K for a black body with its rotation axis sunward. However, Phaethon' s surface temperature would need to reach 1650 K to explain the current anomalous brightening through thermal radiation, so perihelion brightening is not due to surface thermal radiation.

Regarding solar wind effects, Phaethon' s brightening occurs approximately 0.5 days after coronal brightness increases, not perfectly coincident in time. After subtracting coronal background from photometric data, Phaethon' s light curve still shows significant changes before and after brightening. Based on a 2 mag brightness increase, the calculated coronal particle density is 5×10^{14} m^{-3}, far exceeding the actual coronal density of 10^{10} m^{-3} at that location, making this mechanism unable to explain the brightening intensity. Given Phaethon' s large and variable phase angles, phase angle scattering effects were considered. Compared to the Moon' s phase function, Phaethon brightened by more than 1 mag near phase angles of 80°-100°, lasting for 2 days, which contradicts theoretical gradual brightness decay, suggesting brightening is not caused by phase angle scattering. Additionally, specular reflection from rocky asteroid surfaces has been excluded.

4.1 Spectral and Composition Analysis

Phaethon is a B-subtype within C-type asteroids, exhibiting an unusual "blue" spectrum with negative slope. As shown in [Figure 5: see original paper], based on observational spectral properties, Phaethon displays a negative slope in the visible band 0.37-0.7 m without absorption features. Near 0.7-0.75 m, the slope decreases further (becoming bluer). Near-infrared data show minimal variation, with a prominent negative slope at 1 m and an upward concavity after 1.2-1.3 m, with the negative slope gradually flattening to become neutral by 1.8 m. Overall, the slope varies slightly across the entire visible wavelength range but changes more significantly over smaller wavelength intervals.

Initially classified as F-type due to lack of ultraviolet absorption features, Phaethon' s classification has since merged into the B-type category, which exhibits featureless reflectance spectra in the 0.5-1 m range, flat or slightly "blue" (negative slope), similar to B-type asteroids in the Pallas family. Phaethon' s special characteristic is its more pronounced negative spectral slope, leading de León et al. to suggest it could represent a separate classification. Spectral classification and comparisons are discussed further in Section 6.

Phaethon' s spectral absorption varies with location, with slight differences in spectral slope at different rotational phases. Hanuš et al. suggested that Phaethon' s north pole may show distinctly different ultraviolet absorption compared to other regions, while Borisov et al. inferred different polarization properties at the north pole. Further research is needed to determine the physical mechanisms in polar regions and whether such spectral characteristics exist at other wavelengths. Since particle size also affects spectral slope, meteorite type comparisons can be influenced by surface grain size factors. As asteroid surfaces may be heterogeneous, latitude variations in surface properties can cause changes in observational geometry and asteroid orientation. However, Lee et al. found insufficient evidence for surface heterogeneity through spectral studies.

Phaethon' s reflectance spectrum indicates surface composition of severely thermally altered carbonaceous chondritic material, with albedo increasing by about 30% from 1.0 m to 0.5 m and approximately 36% Mg-rich olivine. This may result from heating during perihelion passages that altered surface composition, related to decomposition of phyllosilicates due to extreme heating. Water in carbonaceous chondrites reacts with olivine, pyroxene, and serpentine to form hydrated silicate minerals, while B-type asteroids experience some dehydration, with compositions between hydrated and anhydrous states. The feature at 3 m indicates no hydrated minerals on Phaethon' s surface, likely resulting from high-temperature processing.

Several chondrites have been proposed as possible surface components. Based on near-infrared observations (0.4–2.45 m), Licandro et al. suggested highly thermally processed CI and CM meteorites as the best compositional matches. Madiedo et al., using atmospheric scintillation spectra, inferred Geminid meteorite composition consistent with CM chondrites and found Phaethon' s near-infrared spectrum matches anhydrous CK chondrites well. Clark et al. found the best spectral match with thermally processed CK4 meteorites ALH85002 and EET92002. CK4 meteorites are highly oxidized, containing CAI, olivine, refractory metal sulfides, FeOx, and highly refractory graphite matrix, resulting from extensive hot water circulation reprocessing of original Fe-Mg silicates, sulfides, and complex organics. In related B-type research, asteroid (101955) Bennu' s spectrum best matches CI chondrite Ivuna samples heated above 1000 K. Kareta et al. experimentally demonstrated that Phaethon's surface spectrum from near-ultraviolet to at least 2.5 m is consistent with heated CI chondrites. Recently, Maclennan and Granvik calculated mid-infrared emissivity spectra through spectral mixing models, modeling various mineral species and concluding that Phaethon most closely resembles heated carbonaceous chondrite CY, with consistent olivine abundances. Their phyllosilicates fully dehydrate and dehydroxylate at 300–500 K, converting to olivine at 870–970 K, simulating Phaethon' s high-temperature lithological changes.

4.2 Origin of the Blue Surface

Phaethon' s distinctive relatively "blue" surface may result from large grain sizes in its regolith, surface roughness, thermal alteration, or any combination of these factors. Slope variations in near-infrared data can be interpreted as grain size effects, relevant to polarization measurements and thermophysical modeling calculations. Spectra of meteorite and asteroid materials tend to have more negative slopes (bluer) with increasing effective grain size, as carbonaceous chondrites become bluer with larger grain sizes. Experiments show that carbonaceous chondrites undergo surface sintering and metamorphism at high temperatures, causing surface grain coarsening. If Phaethon' s surface consists of carbonaceous chondrite-like material, this process would occur.

After long-term thermal effects, Fe and organic solids in near-solar regions of Phaethon' s surface layer sublime, leaving no Fe in the spectrum and rapidly increasing the negative slope. Pallas, with similar spectra but lacking comparable thermal environments, may have reduced bluing due to relatively increased nanophase Fe. Lisse and Steckloff proposed that any asteroid on Phaethon-like orbits with perihelia less than 0.15 AU may have blue surfaces, testable through observations of numerous near-Sun asteroids to identify blue surfaces and Fe- and CHON-rich comets. Solar wind continuously exposes fresh surfaces on

Phaethon during each perihelion passage, maintaining surface blueness through sublimation, with calculated Fe loss rates at perihelion of Q_{gas} = 10^{22} mol s^{-1}.

In addition to these components, Na in chondrites volatilizes at high temperatures and carries dust outward. After Fe and Na sublimation, some rocks like pyroxene decompose into SiO and O_2 vapor, leaving solid refractory olivine residues. This sublimation process weakens the solid matrix of pyroxene surfaces, with solids detaching as entrained dust in sublimating gas outflow. This theory also applies to similar-environment asteroids like 2005 UD, with further verification possible through in-situ measurements of Phaethon' s surface near perihelion by the DESTINY+ mission.

4.3 Albedo

Many asteroid geometric albedos are calculated by combining infrared radiation observations with visible photometry. Additionally, since albedo and polarization follow the inverse Umow law, albedo can also be derived from polarization observations. Phaethon' s currently measured albedo range is 0.08-0.13. Based on IRAS thermal infrared data, Tedesco and Desert calculated Phaethon' s albedo as 0.11, higher than typical values for F-type spectral asteroids (0.03-0.07). Hanuš et al. used thermophysical models (TPM) with IRAS and Spitzer data to derive a geometric albedo of 0.122 ± 0.008, higher than Tedesco and Desert' s result. Masiero et al. calculated a geometric albedo of 0.16 ± 0.02, confirming high albedo.

Some researchers have obtained lower albedo results. Zheltobryukhov et al. estimated Phaethon' s geometric albedo in the R filter as 0.075 ± 0.007, consistent with initial F-type classification. Kareta et al. observed a thermal tail at 2.0 m not present at larger heliocentric distances, fitted Phaethon' s thermal radiation tail, and derived an albedo of 0.08 ± 0.01. Currently, radar measurements give Phaethon a diameter of 5.7 km, larger than previous results (5.1 km), which could lead to underestimated albedo.

Phaethon' s surface exhibits strong polarization, meaning theoretically calculated geometric albedo would be lower than values derived from radiation observations. If its albedo is high, Phaethon deviates from the Umow law, where polarization is inversely related to geometric albedo for solar system small bodies, as multiple light scattering is greater on high-albedo surfaces, resulting in weaker polarization. Devogèle et al. derived an albedo of approximately 0.05 from polarization observations, significantly different from Hanuš et al.' s radiometric albedo of 0.122. Combining Phaethon' s strong polarization with the larger radar-observed diameter supports the low albedo case from Kareta et al. Geem et al. derived an albedo of 0.11 from low-phase-angle polarization observations, consistent with high albedo. Albedo controversies may result from heterogeneous surface composition, with grain size and other factors also affecting albedo.

4.4 Polarization Analysis

Polarization measurements of small bodies at different phase angles better reveal surface material properties, aid spectral classification, and can infer water content in C-type asteroids through low-phase-angle polarization observations. Following the determination of Phaethon' s high albedo, polarization observations are needed to assess whether corresponding polarization levels match expectations. Phaethon exhibits high polarization levels, with Devogèle et al. obtaining multi-color polarization curves for phase angles of 36°–116°, showing extremely strong linear polarization at high phase angles, with polarization degree reaching maximum (P_{max}   45%) at approximately 130° phase angle. According to the Umow law, with fixed surface grain size d, empirical formulas relate P_{max} to albedo A: d = 0.03 exp[2.9(lg A + 0.845 lg P_{max})]. Devogèle et al. calculated that Phaethon' s polarization albedo is much lower than the radiometric albedo of 0.122 determined by Hanuš et al., while Geem et al. measured an albedo of 0.11 from polarization, more consistent with high albedo. Geem et al. measured Phaethon' s polarization curve at lower phase angles (8.8°–32.4°), shown in [Figure 6: see original paper], with minimum polarization P_{min} = (-1.3 ± 0.1)% and polarization inversion angle of 19.9° ± 0.3°, with minimum polarization values demonstrating that Phaethon' s surface is closer to anhydrous meteorite conditions.

Maximum linear polarization P_{max} and phase angle are related to surface grain size. When surfaces are dominated by large grains, fewer grains cover the surface, reducing multiple light scattering and resulting in stronger polarization. As described above, Phaethon' s high-temperature sintering process makes high polarization consistent with blue surface characteristics. With constant albedo, larger surface grains produce relatively stronger polarization. Higher surface porosity also leads to stronger polarization. Ito et al. observed Phaethon polarization as high as (50.0 ± 1.1)% at higher phase angles (= 106.5°), estimating surface coverage by 150 m grains, while Geem et al. estimated surface grain diameters of approximately 300 m, differing from thermal model results of millimeter-sized grains. Actual grain sizes require further investigation combining thermophysical modeling, likely indicating surface heterogeneity. Maclennan et al. analyzed heterogeneous surface grain sizes and found Phaethon' s polarization consistent with coarse-grained surfaces in the northern hemisphere.

5.1 Orbital Evolution Model

By taking a reasonable variation range for Phaethon' s current orbital elements and performing identical orbital inversion for different elements within this range, we can understand the multiple possibilities of Phaethon' s past orbital evolution. For example, generating 100 different orbital elements from 1σ deviations relative to Phaethon' s orbital elements for inversion. If multiple stable evolutions share common features, they can indicate the asteroid' s general evolutionary path. [Figure 7: see original paper] shows Phaethon' s dynamical inversion results, selecting 50 clones with small differences (2×10^{-9} in semi-major axis, 2×10^{-8} in eccentricity, 3×10^{-7} in inclination) from approximate clone orbits for inversion. Semi-major axis evolution shows clear signs of planetary encounters, dominated by random walk effects from brief gravitational perturbations caused by planetary encounters, with clone semi-major axes beginning to diverge approximately 4×10^3 years ago. Over approximately 10^5 years shown in [Figure 7a: see original paper], orbital semi-major axis evolution is primarily affected by major planet gravitational perturbations, while eccentricity e and inclination i evolutions show no obvious disturbances but are influenced by long-period frequency variations from accumulated semi-major axis perturbations. Overall, Phaethon' s orbital eccentricity has shown a uniform increasing trend over the past 3×10^5 years.

This study employed the MERCURY6 integrator to calculate Phaethon' s dynamical orbital evolution. As shown in [Figure 8: see original paper], approximately 2×10^3 years ago, Phaethon' s orbital eccentricity reached its maximum, causing its perihelion distance q to be about 0.126 AU, much smaller than the current value (approximately 0.14 AU). Eccentricity reached maximum near 2×10^3 years ago after regular slow increase.

Phaethon' s origin can also be investigated through orbital inversion. The Pallas family is among the most discussed sources for Phaethon. In dynamical mechanism studies, most primitive asteroid families (C-type and B-type) in the inner main belt have nearby secular or mean motion resonances. Among Pallas family asteroids, some are in 8:3 and 5:2 mean motion resonances with Jupiter. Calculations show the minimum size for asteroids at these locations is 4.95 km, comparable to Phaethon' s size, and eccentricity can be further excited at Jupiter resonances to cross Mars or Earth orbits, providing a possible evolutionary path for near-Earth asteroids like Phaethon. Therefore, de León et al. attempted clone numerical integration at Jupiter' s 8:3 and 5:2 MMR positions, evolving 1σ deviations corresponding to Phaethon' s orbital element averages for 1×10^5 years. Results showed approximately 93% of particles would fall into the Sun, about 5% would encounter Jupiter and fall, and only 2% (21 clones) could evolve to Mars-Earth crossing regions. When asteroids enter near-Earth space, their eccentricity begins oscillating between 0 and 0.9, with resonances pumping eccentricity to higher values until crossing near-Earth space. Through inversion, this asteroid can achieve Phaethon-like orbits with approximately 1.2 AU semi-major axis and high inclination, demonstrating that Pallas family fragments could indeed become near-Earth asteroids and evolve into orbits similar to Phaethon. [Figure 9: see original paper] shows the evolution of an effective clone into a Phaethon-like orbit.

Todorović conducted more rigorous dynamical research, finding that from Pallas family' s Jupiter-resonant portions at 5:2 and 8:3 MMR positions, 43.6% and 46.9% of particles, respectively, could satisfy Phaethon-like orbital evolution pathways, more effective than previous studies. This suggests that near-Earth object populations may contain Pallas family evolutionary members with Phaethon-like orbits.

5.2 Thermophysical Model

Thermal radiometry is crucial for studying asteroid physical properties. Thermophysical models can calculate infrared radiation from asteroids at specific orbital positions, and fitting to observations yields parameters including thermal inertia, size D, albedo A, and surface roughness fr. Thermophysical models are divided into two categories. Simple models assume spherical asteroids, including Standard Thermal Model (STM), Near-Earth Asteroid Thermal Model (NEATM), Fast Rotating Model (FRM), etc., where surfaces instantly reach equilibrium under solar radiation, using empirical formulas to calculate different temperature distributions for fitting to obtain albedo and size. The other category treats asteroids as polyhedrons composed of triangular facets, including Classical Thermophysical Model (TPM), Advanced Thermophysical Model (ATPM), and Regolith Simulation Thermophysical Model (RSTPM), which can approximate real asteroid shapes and solve heat conduction equations on each facet with boundary conditions considering multiple solar radiation scattering, inward heat conduction, and outward thermal radiation.

This study used the Advanced Thermophysical Model (ATPM) to investigate Phaethon's thermophysical parameters. Combining Phaethon shape model data, the temperature of any surface facet is determined by:

$$\rho c \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

where , c, and are density, specific heat capacity, and thermal conductivity, respectively. According to energy conservation, the external boundary condition is determined by the sum of solar radiation and radiation from other facets equaling inward heat conduction plus outward thermal radiation:

$$(1 - A_b) F_s \cos\theta / r_h^2 + F_{sc} + (1 - A_{th}) F_r = \varepsilon \sigma T^4 - \kappa \left(\frac{\partial T}{\partial z} \right) \bigg|_{z=0}$$

where A_b is Bond albedo, F_s is solar constant, r_h is heliocentric distance, s is facet visibility coefficient relative to the Sun (s = 1 when illuminated, s = 0 when shadowed), is the angle between incident sunlight and facet normal, F_s = 1367.5 W m^{-2} is the solar constant, F_{sc} is scattering of solar radiation from other facets, and F_r is inter-facet self-heating. For simplification, following Lagerros' standard transformation, temperature T, time t, and depth z are transformed as: x = z/l_s, τ = ωt, u = T/T_e, where l_s = 2√(P_{rot}/(c)) is skin depth, P_{rot} is asteroid rotation period, T_e is effective temperature, transforming the heat conduction equation to:

$$\frac{\partial u}{\partial \tau} = \frac{\partial^2 u}{\partial x^2}$$

Boundary conditions become:

$$(1-A_b)F_s\cos\theta/r_h^2+F_{sc}+(1-A_{th})F_r=\varepsilon\sigma T^4-\frac{\kappa T_e}{l_s}\left(\frac{\partial u}{\partial x}\right)\bigg|_{x=0}$$

where Θ is thermal parameter: Θ = Γ/(σT_e^3)√(ω/(c)), with Γ = √(c) being thermal inertia. By solving these equations, surface temperature distribution T is obtained, and theoretical radiation flux F_λ is calculated using Planck function B(λ, T_i) and visibility factors f_i: F_λ = Σf_{iB}(λ, T_i).

This study fitted Phaethon infrared data from WISE, Spitzer, IRAS, AKARI, and UKIRT (totaling 67 observation epochs, detailed in). Spitzer data were abundant but observed for only 10 minutes; to avoid overweighting in fitting, they were binned by averaging to calculate radiation flux values at integer wavelengths (detailed in). WISE full-band observations from 2010 were used, considering only W3 and W4 bands (12 m and 22 m), along with multi-band infrared data from IRAS and UKIRT.

Surface roughness significantly affects thermal radiation characteristics, as rough surfaces cause solar radiation shadowing and local temperature increases while making thermal radiation directional. This study used hemispherical crater models to simulate rough surfaces, with fr representing roughness (crater area proportion to total facet area). Effective Bond albedo represents reflection from rough and smooth surfaces:

$$A_{eff}=f_r\left(\frac{2}{3}-A_b\right)+(1-f_r)A_b$$

Bond albedo relates to geometric albedo as A_{eff} = p_v q_{ph}, where q_{ph} = 0.29 + 0.684G represents phase integral, G is slope parameter, and geometric albedo relates to diameter through:

$$D_{eff}=\frac{1329\times10^{-H_v/5}}{\sqrt{p_v}}$$

Under these assumptions, theoretical radiation flux contains three free parameters: thermal inertia, roughness, and geometric albedo, i.e., F_λ = F_λ(Γ, f_r, p_v). During fitting, we searched parameter space (Γ, f_r, p_v) with thermal inertia Γ ranging 0-500 J m^{-2} s$^{-0\cdot5}$ K^{-1} and roughness 0-1, using least squares fitting. Parameters corresponding to minimum ^{2} value are optimal:

$$\chi^2=\sum\frac{[F_{\lambda i}(\Gamma,f_r,p_v)-F_{obs}]^2}{\sigma_i^2}$$

with degrees of freedom n - 3.

As shown in [Figure 10: see original paper], we calculated thermal inertia of $550^{+320}\,{}_{160}$ J m^{-2} s$^{-0\cdot5}$ K^{-1}, albedo of $0.1253^{+0\cdot0034}\,{}_{0\cdot0020}$, and corresponding diameter of $5.160^{+0\cdot040}\,{}_{0\cdot0069}$ km, with minimum ^{2} value of 3.590. Due to extensive data, fitting degrees of freedom are large but comparable to and relatively lower than previous work, consistent with existing thermophysical parameter fits. Phaethon’ s strong perihelion activity may cause smaller regolith components to leave the surface, leaving larger rock structures and resulting in higher surface thermal inertia than other asteroids. We compared results with other literature calculations of Phaethon thermal inertia (detailed in).

6.1 Comet and Asteroid Classification Discussion

Comets and asteroids are distinct small bodies, while active asteroids represent a strict cross between asteroids and comets, often called “main-belt comets.” Three classification distinctions exist: observationally, small bodies with unbound atmospheres from volatiles are comets, otherwise asteroids; compositionally, comets are ice-rich bodies formed beyond the protoplanetary snow line, while asteroids are ice-free bodies formed within the protoplanetary disk; dynamically, researchers distinguish comets from asteroids primarily through dynamical parameters, most commonly the Tisserand parameter relative to Jupiter:

$$T_J = \frac{a_J}{a} + 2\sqrt{\left[\frac{a}{a_J}(1-e^2)\right]}\cos i$$

where a, e, and i are orbital semi-major axis, eccentricity, and inclination (relative to Jupiter’ s orbit), and a_J = 5.2 AU is Jupiter’ s semi-major axis.

Jewitt et al. defined active asteroids as: (1) semi-major axis a < a_J; (2) T_J > 3.08; (3) small bodies showing mass loss signs, such as comet-like tails. Activity mechanisms may include sublimation, impacts, rotational disruption, thermal fracturing, etc. [Figure 11: see original paper] shows statistical results of known active asteroid activity mechanisms. Although Phaethon’ s activity is well-established, whether it is more comet-like or asteroid-like requires further discussion.

Dynamical analysis shows Phaethon’ s Tisserand parameter T_J = 4.509, far above the dividing line, indicating asteroid orbital characteristics. Dynamical simulations suggest Phaethon likely originated in the main belt like most near-Earth asteroids, while comets typically originate from the Kuiper Belt or Oort Cloud—a significant distinction. Compared to typical cometary nuclei, Phaethon has higher albedo, bluer optical and near-infrared spectral features, and higher bulk density. Geminid meteor shower analysis indicates meteorite densities of 0.7-1.3 g cm^{-3}, lower than typical cometary meteorite densities, confirming Phaethon is not a typical comet.

In spectral classification, initially F-type asteroids showed comet-like characteristics. Although Phaethon was once considered F-type, more studies suggest this is uncertain. Historical F-type asteroids showed anomalously low polarization spectral inversion angles around 17°, while Phaethon’ s observed polarization inversion angle is 19.9° ± 0.3°, slightly deviating from F-type classification. In albedo, Zheltobryukhov et al. estimated Phaethon’ s geometric albedo in R filter as 0.075 ± 0.007, seemingly consistent with dark F-type asteroids. However, Hanuš et al. derived a geometric albedo of 0.12 using thermophysical models, higher than typical cometary albedo and F-type values (0.03–0.07), but consistent with B-type asteroids comprising the Pallas collision family. Whether albedo supports Phaethon’ s classification requires deeper investigation.

Devogèle et al. fitted polarization spectra, finding higher correlation between Phaethon and B-type body Pallas. Fitting Phaethon and other F-type asteroid spectra produced deviations from Phaethon’ s polarization spectrum, while modern B-type fitting matched Pallas polarization data well with significantly improved best-fit rms. In summary, as an active asteroid, Phaethon’s properties are more asteroid-like and more similar to B-type asteroid Pallas, even though Phaethon’ s special negative spectral slope makes it bluer than other B-type asteroids.

6.2 Pallas Family Evolution Discussion

Lemaitre and Morbidelli first noted the Pallas family as a possible Phaethon source. Pallas is the third-largest body in the asteroid belt, with mean diameter 550 km, semi-major axis 2.77 AU, classified as B-type. Identifying it as Phaethon’ s source requires satisfying dynamical mechanisms and physical properties, meaning Pallas family members of Phaethon’s size could form planet-crossing orbits to become highly inclined near-Earth asteroids, with similar compositions reflected in spectral similarity. Kareta et al. proposed that Phaethon’ s origin is fundamentally a question about its current and past activity nature.

In dynamical mechanism studies, Pallas family asteroids exist at Jupiter’ s 8:3 and 5:2 MMR resonance positions, with minimum sizes of 4.95 km, comparable to Phaethon’ s size. Asteroids here can be excited to cross Mars or Earth orbits through eccentricity enhancement, representing a reasonable evolutionary path. As described above, de León et al.’ s clone numerical integration showed 2% of clones could evolve to Mars-Earth crossing orbits and ultimately achieve Phaethon-like orbits. Todorović also demonstrated the existence of Pallas family evolutionary members with Phaethon-like orbits in near-Earth object populations.

Nevertheless, Phaethon cannot be conclusively identified as a Pallas evolutionary member. Maclennan et al. argued that no convincing dynamical evidence indicates Pallas is most likely Phaethon’ s parent body, suggesting inner main belt Svea family asteroids with inclinations around 16° may better match Phaethon’ s high-inclination evolutionary characteristics. Using the SWIFT RMVS integrator and OpenOrb software to calculate clone orbital elements, they found multiple close encounters with inner planets make inclination parameters random, rejecting inclination-based similarity support for Pallas as Phaethon’ s parent body. Even if Phaethon’ s mean inclination 5 Myr ago approached Pallas’s 33°, large variations from inner planet influences make averages statistically insignificant. Svea itself is classified as C-type, with some B-type family members near the 3:1 Jupiter MMR resonance position, also capable of evolving to near-Earth orbits. Notably, if Phaethon’ s orbit changed during Geminid stream formation, orbital inversion would be significantly altered.

In spectral comparison, [Figure 12: see original paper] shows Phaethon has some similarity with Pallas and its family members in visible and near-infrared spectra. Data near 3 m indicate Pallas composition matches heated CM chondrites and is similar to CR chondrites, while Phaethon’ s near-infrared spectrum currently better matches CK and CI meteorites. Atmospheric scintillation spectra indicate Geminid meteorite composition matches CM chondrites, showing some compositional similarity with Pallas. Differences within dashed boxes in [Figure 12a: see original paper] arise from size and surface grain differences. As carbonaceous chondrites become bluer with increasing grain size, larger bodies retain finer cohesive surface grains while smaller bodies lose fine grains and become covered by coarser grains, making Phaethon bluer than Pallas. Additionally, Phaethon’ s sintering and Fe removal further explain its bluer characteristics compared to Pallas.

Although Phaethon’ s geometric albedo remains controversial, Hanuš et al. derived high albedo of approximately 0.122 ± 0.008, close to Pallas’ s high albedo of 0.145. Devogèle et al. derived Phaethon’ s phase-polarization curve similar to asteroid Pallas. Kareta et al. argued that spectral differences cannot be ignored, opposing the Pallas family as Phaethon’ s source. In summary, Phaethon shows similarities with Pallas in orbital and surface properties, but controversies remain, and Phaethon may originate from other main belt families, such as the Svea family.

6.3 PGC Relationship Research

Asteroids (155140) 2005 UD and (225416) 1999 YC, having similar orbital elements and colors to Phaethon, are considered possible fragmentation pieces or former components of a common body, especially given color similarity and size ratio between Phaethon and 2005 UD supporting their connection. Together with the Geminid meteor stream, they are collectively called the Phaethon-Geminid Complex (PGC). The PGC may be ancient, while the Geminid meteor stream’ s dynamical lifetime does not exceed several thousand years. Beech analyzed three Geminid fireballs, finding stream ages of (1–4) × 10^3 years. Phaethon had unique perihelion and eccentricity changes 2000 years ago with minimum perihelion distance, possibly related to Geminid meteor shower origin. Jewitt et al. suggested the Geminid meteor shower may result from a catastrophic event occurring within thousands of years.

The Geminid meteor stream is denser than typical cometary streams, with asymmetric spatial distribution near peak, composed of particles ranging from 10 m to 4.5 cm. Stream structural characteristics include: dust particles eject from points around the parent orbit rather than a single point; particles eject from the Sun-facing hemisphere; ejection velocity depends on particle size, with larger particles having lower velocities. These properties create the stream’ s unique double-peaked activity profile. After particle ejection, reaction forces affect the parent asteroid’ s orbit and attitude. Ryabova quantitatively characterized the Geminid stream’ s radiant distribution using semi-analytical numerical models applicable to meteor shower observation simulations. Beyond ground observations, PSP observed Geminid dust trails, deriving dust masses of 10^{10}-10^{12} kg, likely representing partial meteoroid accumulation near Phaethon.

Regarding perihelion mass loss, the most discussed causes are thermal fracturing assisted by rotation and radiation pressure removal, or Na sublimation driving. Kasuga and Masiero conducted space-based thermal infrared observations of PGC-related asteroids, calculating Phaethon mass loss rate upper limit of 2 kg s^{-1}, and 0.1 kg s^{-1} for 2005 UD and 1999 YC, differences difficult to maintain through steady state, supporting catastrophic event formation theory for the Geminid stream.

Cukier and Szalay simulated expected stream positions under Phaethon sudden disruption events and cometary dust activity conditions, using 1 km s^{-1} velocity-separated dust to simulate disruption events and size-dependent ejection velocity for comet-like activity, with zero-velocity dust as control. Results showed stream positions best match disruption formation rather than cometary mechanisms, suggesting Geminid stream formation through catastrophic destruction near perihelion. However, quantitative study of thermal fracturing mass loss mechanisms requires more space experiments due to differences between laboratory and actual space environments.

Beyond Geminid stream relationships, whether Phaethon and the other two asteroids originate from the same parent body warrants further study. 2005 UD has rotation period 5.2 h, perihelion distance 0.16 AU, with color indices similar to Phaethon. 1999 YC has rotation period 4.5 h, perihelion distance 0.24 AU. Spectrally, Phaethon and 2005 UD show greater similarity, both currently B-type with extremely similar visible spectra and blue characteristics, while 1999 YC’ s spectrum indicates C-type with redder overall color. Additionally, the period (3.6 h) and size ratio of the Phaethon-2005 UD pair match Pravec et al.’ s asteroid pair spin-fission formation model, suggesting 2005 UD may be a fragment separated from Phaethon.

As shown in [Figure 13: see original paper], Devogèle et al. compared polarization phase curves and spectra between the two asteroids, finding nearly identical polarization curves for Phaethon and 2005 UD but significant differences from Bennu. NEOWISE thermophysical modeling indicated similar surfaces, giving 2005 UD albedo p_v = 0.10 ± 0.02, size 1.3 ± 0.2 km, and thermal inertia $300^{+120}{}_{110}$ J m^{-2} s^{-1}/^{2} K^{-1}. Studies show Phaethon surface grain sizes range 3-30 mm, while 2005 UD ranges 0.9-10 mm, possibly due to Phaethon’ s thermal environment ejecting finer grains or surface composition thermal inertia differences. Near-infrared reflectance spectra show differences, with 2005 UD having more positive “red” slope compared to Phaethon’ s blue negative slope. Compositionally, Phaethon resembles CI chondrites, while 2005 UD shows poor matches, and no meteorite has been found that fits both asteroid spectra at different temperatures, even accounting for different thermal environments.

Studies show strong orbital evolution correlation between Phaethon and 2005 UD over thousands of years, with similar orbital element changes approximately 4600 years ago. 1999 YC’ s orbital inversion differs from the other two asteroids, though Ohtsuka et al. suggested that if differences can be explained by orbital perturbations, the three asteroids may still be related. Hanuš et al. repeated orbital evolution calculations for 2005 UD using nominal and 50 clone orbits, confirming orbital similarity. As shown in [Figure 14: see original paper], Maclennan et al. used the SWIFT integrator to perform clone orbital inversion integration for 1000 random Phaethon and 2005 UD orbits, calculating best-fit orbital elements in the least-squares sense throughout orbital history. All clone orbits underwent similar periodic eccentricity variations, providing possibility for fission theory. After multiple encounters with inner planets entering near-Earth object regions, inclination undergoes major changes, making current orbital similarity particularly special.

However, even if from the same body, these two bodies may have separated from a common parent approximately 10^5 years ago, meaning their formation may be unrelated to the meteor stream. Additionally, Ryabova et al. questioned this common origin dynamically, arguing that if related, fragments would exist in each other’ s debris streams. They found 2005 UD’ s fragment intersection with Phaethon is distant, while 1999 YC’ s fragment separation intersection is closer to Phaethon, but this does not demonstrate strict correlation. Using the DSH criterion to quantify orbital similarity, Phaethon and 1999 YC have DSH 1.0, exceeding the maximum value of 0.058 for correlation judgment, thus denying their correlation.

7. Expected Missions and Prospects

Current Phaethon research is relatively comprehensive among active asteroids, but controversies remain in thermophysical models, surface composition, and anomalous brightening mechanisms, requiring further in-depth study. Targeted exploration missions can provide more precise data support. JAXA’ s DESTINY+ mission has selected Phaethon as a target, scheduled for launch in 2028, with planned flyby and possible extension to 2005 UD.

DESTINY+ aims to achieve high-resolution imaging, close flyby, high-precision navigation, and wide-range observations of Phaethon. DESTINY+ carries three scientific payloads: Tracking Camera (TCAP), VIS-NIR Multi-band Camera (MCAP), and Dust Analyzer (DDA), for in-situ detection of Phaethon’ s surface and composition near perihelion. TCAP and MCAP will perform high-speed

(36 km s^{-1}) flyby imaging at closest approach of 500 ± 50 km; DDA, developed by a University of Stuttgart team based on Cassini' s Cosmic Dust Analyzer (CDA), will directly measure dynamical parameters and elemental abundances of dust particles near Phaethon.

DESTINY+ science objectives include investigating cosmic dust properties and origins, measuring physical properties and chemical composition of interplanetary and interstellar dust particles near 1 AU during deep space cruise, and conducting geological observations of Phaethon to understand active asteroid dust ejection mechanisms and surface composition changes. It will launch on an Epsilon rocket into Earth-elliptical orbit, then use electric propulsion to raise orbit to reach the Moon. After multiple lunar gravity assists to escape Earth' s gravity, electric propulsion will take it to Phaethon for flyby observation. At flyby, geocentric distance will be 1.72 AU, heliocentric distance 0.87 AU, after which DESTINY+ may proceed to 2005 UD.

Before flyby, detailed understanding of Phaethon' s size, shape, albedo, and rotation state is needed to assess dust and debris environment. According to Masiero et al., dust analyzers at approximately 500 km from Phaethon may encounter up to 10^3 micrometer-sized dust particles. However, due to sparse dust, direct dust impact probability for PSP and DESTINY+ is low. In-situ dust activity observations will provide important indicators for studying active asteroid properties and may reveal activity signs from 2005 UD. DESTINY+ direct observations of Phaethon' s surface will yield more precise shape models and establish thermophysical models for geometric albedo, helping better understand Phaethon' s thermal history and formation of current physical properties.

In small body exploration missions, China' s Chang' e-2 successfully performed a flyby of near-Earth asteroid (4179) Toutatis on December 13, 2012, at closest approach 770 ± 120 m from the asteroid surface, revealing its physical properties, rotation characteristics, internal structure, and formation mechanism with major international impact. Future active asteroid missions include China' s Tianwen-2 probe scheduled for 2025 launch, targeting active asteroid 311P. The mission plans to sample and return from near-Earth asteroid 2016 HO3, then proceed to 311P for rendezvous observation. With size 320–580 m, scientific investigation will focus on active asteroid formation and evolution, gas activity mechanisms, etc. The Tianwen-2 mission is a major planetary exploration project and a landmark mission in China' s space power construction journey, laying important foundations for subsequent deep space exploration missions to Jupiter and beyond.

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