INVESTIGATING THE EXISTENCE OF THE YARKOVSKY EFFECT FROM ASTEROIDS' PHYSICAL AND ORBITAL PROPERTIES

How do asteroids' physical and orbital properties validate the existence of the Yarkovsky effect as a non-gravitational force?

Subject: Physics

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CONTENTS

1. INTRODUCTION

It is known that the Sun and asteroids' gravitational pull causes a consistent circular motion for its orbital path. However, the Yarkovsky effect as a small but significant force deviates asteroids' regular orbital path after millions of years due to a non-gravitational phenomenon. Quantifying and modelling this seemingly unpredictable effect helps accurately predict asteroids' orbital paths in the future, and prevent potential collision risks towards the Earth. For instance, NASA's OSIRIS-Rex spacecraft was sent to asteroid Bennu, a near-earth asteroid (NEA) to understand one of the closest known asteroids to Earth. Although the probability of Bennu colliding with Earth is very low in 2182, NASA's investigation reveals the unpredictable nature of the Yarkovsky effect along with the Sun's emission of heat, contrasting the clearer nature of the gravitational force considering usually only mass and distance.[1] Altogether, this describes the Yarkovsky effect: a small force caused by sunlight that creates a tiny thrust and accelerates asteroids smaller than about 30 to 40 kilometers in diameter.[2] Therefore, **how do asteroids' physical and orbital properties validate the existence of the Yarkovsky effect as a non-gravitational force?** The Yarkovsky effect is further exemplified as asteroids are treated as a blackbody, which almost completely absorbs sunlight's thermal radiation and re-emits its photons over time — applying Newton's third law, the re-emission acts as a recoil force that pushes the asteroid's motion in the opposite direction — to alter the orbital trajectory as shown in Figure 1. To validate the existence of the Yarkovsky effect, it is essential to examine the physical and orbital properties of asteroids that are independent of gravitational force, to demonstrate the significance of how thermal radiation impacts an asteroid's orbit.

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[1] Jet Propulsion Laboratory, "NASA Spacecraft Provides Insight into Asteroid Bennu's Future Orbit."
[2] David Vokrouhlický et al., "The Yarkovsky and YORP Effects," 1.

2. PROGRADE AND RETROGRADE MOTIONS

Figure 1: Dependence of the direction of the Yarkovsky force upon asteroid spin state.[3]

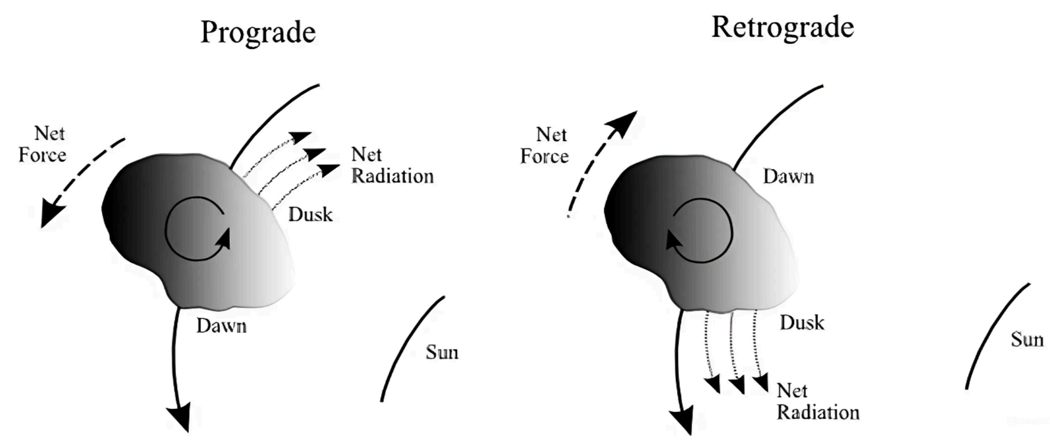


Figure 1 illustrates thermal radiation disturbing asteroids' regular orbit created by the gravitational force of an asteroid and the Sun. These orbital properties are important in determining the momentum of an asteroid after re-emitting photons from the Sun. For instance, asteroids in prograde rotation or the same direction as its orbit, absorb new sunlight at dawn when cold. Then, the Sun warms up the surface until dusk when it re-emits photons behind its path. The prograde rotation results in net radiation towards the Sun, resulting in an opposite motion that propels the asteroid, expanding the orbit's elliptical shape. In contrast, retrograde rotations result in asteroids coming closer to the Sun as the re-emission radiation will be outwards, decreasing the eccentricity. While the net radiation for every diurnal (daily) cycle seems trivial, the momentum from the photons accumulates over millions of years and can perhaps change an asteroid's path. Overall, the diagram only represents an asteroid from a two-dimensional perspective. Accordingly, theoretical calculations and practical observations can ensure that it accounts for the three-dimensional spin, as well as the consideration that asteroids have mostly jagged and inconsistent surfaces, which may affect calculations.

[3] Hyland David et al., "NEA Mitigation via the Yarkovsky Effect," 2.

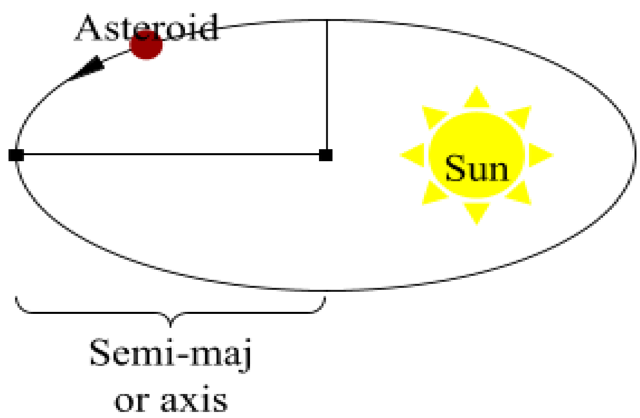
3. PHYSICAL AND ORBITAL PROPERTIES

Many components such as magnetic fields, space dust, plasma interactions, and other external variables may prevent scientists from making accurate predictions about a model. Hence, gathering astrometric data from photometry and infrared spectra does not always provide the most accurate information about the physical properties and orbital dynamics of these asteroids. Graphical representations can be used to illustrate possible detections and reveal the visual differences of various asteroid components. These physical and orbital properties of asteroids that are affected by the Sun's thermal radiation will be explored throughout the paper: semi-major axis drift rate, eccentricity, bulk density, thermal inertia, SNR and S.

I. Semi-Major Axis Drift Rate:

An orbital property that will be explored is the secular (long period) change in the semi-major axis: the longest radius of an elliptical orbit as illustrated in Figure 2. Gravitational force theoretically maintains a constant orbital shape and is a much stronger force than thermal radiation. In turn, the semi-major axis is ideal for studying the Yarkovsky effect, as it isolates the effect of thermal radiation from gravity, allowing a more accurate representation; although there are still some perturbations, they are not as influential of a force as gravity. This would cause a rate of change in the semi-major axis (a) of an asteroid's orbit with respect to time (t), which can increase or decrease the length of the axis based on the prograde or retrograde rotation. The thrust produced when the asteroid re-emits photons from the Sun theoretically changes the semi-major axis by creating a force that pushes an asteroid's orbit inwards or outwards as shown in Figure 1. Semi-major axis drift rate ($\frac{da}{dt}$) is in astronomical units per million years ($auMy^{-1}$), to highlight the small, but significant and cumulative orbital changes over extended time periods.

Figure 2: Semi-major axis of an asteroid's orbit.[4]



II. Eccentricity:

A similar measurement to the semi-major axis is eccentricity (e), to confirm the effect of thermal radiation on the shape of an asteroid's orbit. It measures how stretched an asteroid's orbit is, where an orbit with $e = 0$ is perfectly circular, while higher values depict an orbit that is more elongated or oval-shaped.

III. Bulk Density:

To determine the reason for an asteroid's $\frac{da}{dt}$, it is important to account for how well an asteroid re-radiates thermal energy. In particular, as the Yarkovsky effect is based on the effect of sunlight, two related variables can be measured: bulk density and thermal inertia.

$$\rho = m \div V$$

Bulk density (ρ) is in kgm^{-3} being the asteroid's mass (m) divided by the total volume (V) including solid and void spaces.[5] The higher an asteroid's bulk density, the more heat it can store before it re-emits into a net radiation during the dusk. This could be attributed to an asteroid's

[4] Google.
[5] Nihar Mohanta and Meena Murmu, "Bulk Density."

thermal inertia, however, bulk density accounts for only mass and volume; thermal inertia is based on the physical, chemical and material properties that can change its ability to re-emit an amount of thermal radiation.

IV. Thermal Inertia:

Thermal inertia (I) is in $Jm^{-2}K^{-1}s^{-0.5}$ where thermal conductivity (k) is in $Wm^{-1}K^{-1}$, bulk density (ρ) is in kgm^{-3} and specific heat capacity (c) is in $JK^{-1}kg^{-1}$. It measures an asteroid's ability to store heat and resist temperature changes based on its conductivity.

$$I = \sqrt{k\rho c}$$

High thermal inertia results in a lower semi-major axis drift rate as the temperature from thermal radiation is stored better. This suggests that absorbed photons take more time to be re-emitted, presenting a weaker radiation force, and vice versa for those with lower thermal inertia. The extent of how much thermal radiation affects an asteroid's orbital path is affected not only by its type of rotation but also by how well it can maintain its temperature gradient and convert the radiation into a magnitude of force.

V. SNR and S:

The reliability of the data acquired from one asteroid in space is quantified as the signal-to-noise ratio (SNR). The higher the SNR, the more reliable the data is for that specific asteroid.

$$SNR = \frac{\mu}{\sigma}$$

The population mean (μ) signifies the signal's power in decibels (db), and the standard deviation of data (σ) in dB is the power of background noise.[6] Namely, an SNR of x shows that the signal

[6] *Geeks for Geeks*, "Signal to Noise Ratio Formula."

is x times stronger than the noise which represents the external factors that may affect the final value of a signal. Therefore, depending on the extent of the SNR, the data retrieved may not be reliable for precise measurements, as noise could disturb the signal with great uncertainty. Next, the relative SNR (S) represents the relative SNR to its maximum potential power.

$$S = \frac{SNR}{SNR_{max}}$$

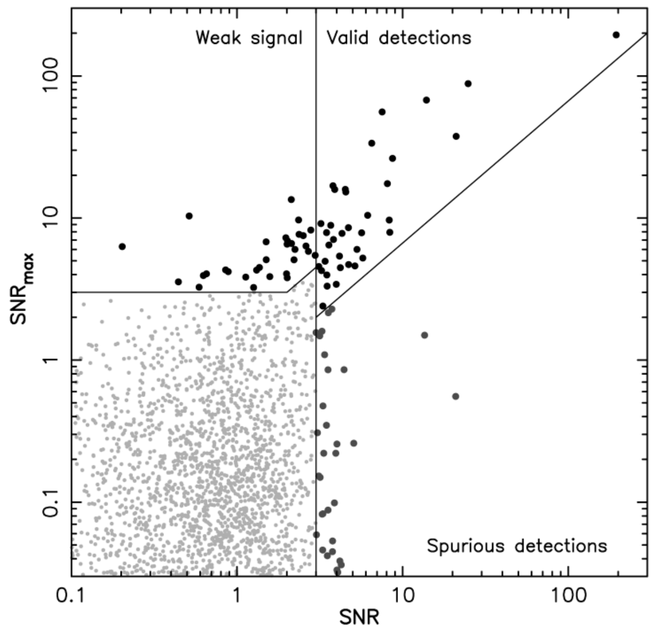
S = 1 signifies that the values retrieved are at the maximum expectation of SNR according to calculations, and proves that the data points are the most reliable for that specific asteroid. S < 1 means that the SNR provided is not the best possible SNR, meaning it is detected with greater uncertainty than SNR_{max}.

4. DATA ANALYSIS

4.1. DISTRIBUTION OF ASTEROIDS' SNR AND SNR_{max}

In the process of retrieving data from space, there are many invalid data points, which suggest that with the boundless amount of asteroids in the solar system, some asteroids may be too far away from the Sun, or have some unknown physical or thermal properties that increase the chances for uncertainty and noise. Hence, the accuracy of the $\frac{da}{dt}$ retrieved for the invalid asteroids may have inaccurate values as they are more difficult to detect with noise. Figure 3 represents the NEAs detected with various levels of uncertainty and noise levels that may impede findings. Data points in the top right section with SNR and $SNR_{max} \geq 3$ are categorized as "valid detections" with the most clarity. The points in the bottom right with SNR ≥ 3 and SNR_{max} ≤ 3 are "spurious detections," as the SNR_{max} is much below the theoretical SNR; it is thus unlikely

Figure 3: SNR and SNR_{max} representing four sectors of detection as of December 2014.[7]



for these asteroids to be able to represent the Yarkovsky effect because of their considerably greater mass, which may be the reason for the errors. The "weak signal" data points on the top left have low SNR but higher SNR_{max}, indicating that the data is unreliable because the expected maximum SNR value could be much higher. With those SNR values, it hints that there is too much background noise increasing the chances for uncertainty. The bottom left section constitutes gray, non-conclusive data points with SNR and SNR_{max} too low to extrapolate data and make reliable conclusions about the existence of the Yarkovsky effect. The low SNR detections could be caused by the anisotropic thermal radiation from uneven surfaces of an asteroid.[8] Anisotropic heating relates to how one side of an asteroid gets heated when facing the Sun while the other side cools down as illustrated in Figure 1. In contrast to isotropic radiation where it is uniform in all directions, anisotropic heating varies in its intensity in every direction. The sporadic heating may be created by asymmetric surfaces, such as the rough mountainous asteroids, and some surfaces may be more thermally conductive, which may change the way an

[7] David Vokrouhlický et al., "The Yarkovsky and YORP Effects," 11.
[8] Karolina Dziadura et al., "The Yarkovsky effect and bulk density of NEAs from Gaia DR3," 2.

asteroid reacts to thermal radiation. Accordingly, the lower SNR values could be attributed to the rough shapes, craters or asteroids that make the re-emission of photons more irregular, increasing the noise and making it harder to accurately detect if the Yarkovsky effect exists. This is similar to when measuring the bulk density of Bennu, which calculates the average density of the entire asteroid. The bulk density around all regions of an asteroid is never uniform, which may also affect the amount of noise created when data is retrieved from space. Moreover, as the detections were taken before December 2014, advanced instruments such as the James Webb telescope were not yet invented.[9] Although technology is more reliable today, the sensitivity and calibration of these detections could have been the reason for the substantial noise levels demonstrated before 2014. Consequently, to confirm the existence of the Yarkovsky effect, it is necessary to ignore the spurious detections, weak signals, and non-conclusive data points, isolating the valid detections to understand what is behind the strong signal detected.

4.2. VALID YARKOVSKY EFFECT DETECTIONS

Figure 3 summarizes a section of valid asteroid detections that may represent the Yarkovsky effect. The full list of detections in Table 4 presents 36 asteroids with an SNR ≥ 3, where the signal is 3 times stronger than the noise.[10] Although some S values are much lower than 1 (meaning that the maximum expected theoretical SNR could be much higher), the SNR values above 3 are reliable enough as they demonstrate a strong identifiable signal. In one case, for 3908 Nyx, the S

[9] Margherita Bassi, “James Webb Telescope Confirms the Universe Is Expanding Faster Than We Thought—and Scientists Still Don’t Know Why.”
[10] See Appendix A.

= 1.1 surpassed theoretical expectations, which reinforces the reliability of its SNR and proves the unpredictability of the Yarkovsky effect as many inconsistencies in asteroids' environment can change their surrounding noise levels.

Table 4: Valid Yarkovsky effect detections as of December 2014 (see Appendix A for full list).[11]

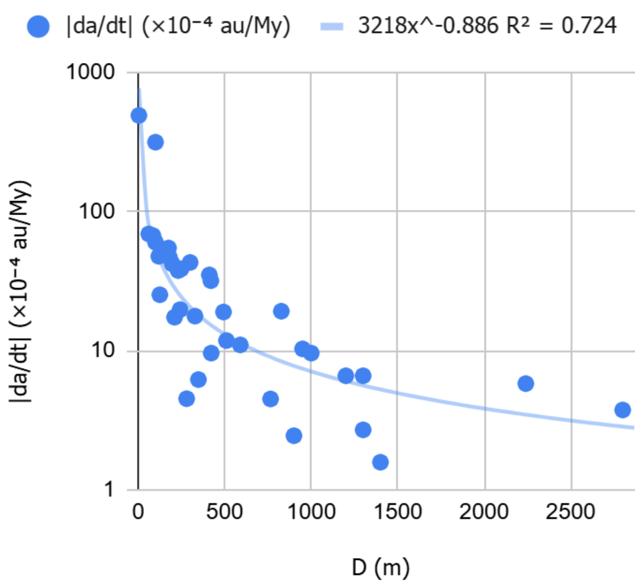
Object	D (m)	da/dt ($\times 10^{-4}$auMy^{-1})	SNR	S
101955 Bennu	493	-18.95 ± 0.10	194.6	1
2340 Hathor	210	-17.38 ± 0.70	24.9	0.3
152563 1992 BF	510	-11.82 ± 0.56	21	0.6
2009 BD	4	-489 ± 35	13.9	0.2
2005 ES70	61	-68.9 ± 7.9	8.7	0.3
4179 Toutatis	2800	-3.75 ± 0.45	8.4	1.1
2062 Aten	1300	-6.60 ± 0.80	8.3	0.9
1999 MN	175	54.6 ± 6.8	8.1	0.5
6489 Golevka	280	-4.52 ± 0.60	7.5	0.1
1862 Apollo	1400	-1.58 ± 0.24	6.5	0.2
2006 CT	119	-47.6 ± 7.7	6.2	0.6
3908 Nyx	1000	9.6 ± 1.7	5.8	1.1
2000 PN8	130	49.3 ± 8.7	5.7	0.7
162004 1991 VE	827	19.2 ± 3.6	5.3	0.9

Next, Table 4 confirms the effect of thermal radiation on asteroids with prograde and retrograde rotations resulting in the positive and negative $\frac{da}{dt}$ respectively. The gravitational and centripetal force of an asteroid and the Sun normally keeps a regular orbital path, however, these influences reveal how an asteroid's re-emission of sunlight can alter its trajectory without the influence of gravitational force, supporting Yarkovsky's theory. This shows that the semi-major axis drift rate is based on an asteroid's rotation direction and orbital dynamics, while still considering physical properties; gravitational and centripetal force depends mainly on mass and distance from an object, not on how the asteroid spins. This instance further validates the existence of the Yarkovsky effect where asteroids are affected by non-gravitational perturbations on top of

[11] David Vokrouhlický et al., "The Yarkovsky and YORP Effects," 10.

gravity. The asteroids labelled with valid SNR values exhibit a semi-major axis drift rate without significant external noise such as gravitational perturbations, that could have overpowered the detections in the other categorized detections in Figure 3.

Figure 5: Semi-major axis versus diameter based on 36 valid detections.[12]



The valid detections provide a better focus on the effect of sunlight and thermal radiation without substantial uncertainties when detected by photometric and infrared devices. One instance supports the theory that the Yarkovsky effect is more prevailing on smaller asteroids: 2009 BD and 2005 ES70 with a diameter of 4 m and 61 m respectively have much higher absolute $\frac{da}{dt}$ values compared to larger asteroids such as 4179 Toutatis with 2800 m. Figure 5 (using the full list of 36 data points continued in Table 4) demonstrates the inverse power-law relationship with the semi-major axis drift rate and diameter, validating the presence of the Yarkovsky effect with a strong coefficient of determination (R^2). The phenomenon is particularly prevalent on smaller asteroids as they have the highest drift rates. Asteroids with smaller diameters correspond to a lower surface area, yet the graph shows that they are still able to absorb enough sunlight to release heat, and result in greater semi-major axis drift than larger asteroids. Larger asteroids, despite having more surface area to absorb more thermal radiation experience less motion, which altogether presents a challenge in understanding the Yarkovsky

[12] Google.

effect and why smaller asteroids, despite their lower surface area, have stronger re-emission forces that result in greater orbital drift. From this, it can be deduced that mass may also affect the amount of re-emission force based on Newton's second law; a lower mass results in a higher acceleration, which can be one reason why smaller asteroids experience a greater orbital drift from the Sun's thermal radiation. Then, it is essential to compare the relationship between surface area and mass by estimating an asteroid's shape as a sphere.

Surface area (A) of a sphere with radius (r) and diameter (D):

$$A = 4\pi r^2$$

$$A = \pi D^2$$

Mass (m) of a sphere with density (ρ) and volume (V):

$$V = \frac{4}{3}\pi r^3$$

$$V = \frac{\pi D^3}{6}$$

$$m = \rho V$$

$$m = \rho\frac{\pi D^3}{6}$$

Surface area-to-mass ratio:

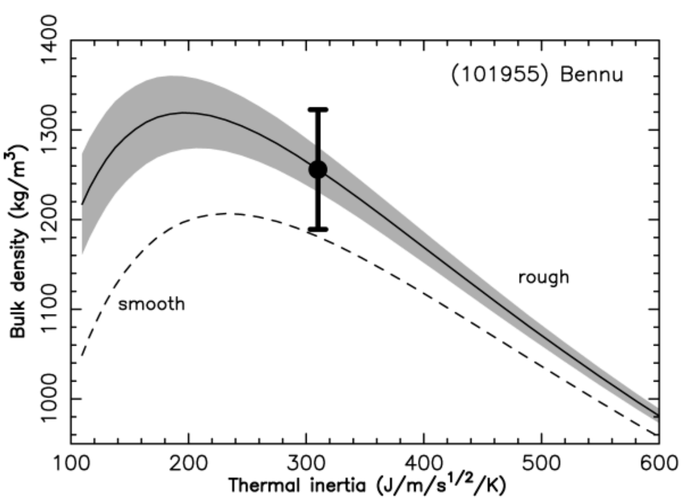
$$\frac{A}{m} = \frac{\pi D^2}{\rho\frac{\pi D^3}{6}}$$

$$\frac{A}{m} = \frac{6}{\rho D}$$

$$\frac{A}{m} \propto \frac{1}{D}$$

The surface area-to-mass ratio of an asteroid is inversely proportional to its diameter. This shows that asteroids with smaller diameters experience more exposure to the Sun with their greater surface area relative to their mass, compared to larger asteroids. This allows smaller asteroids to convert the radiation to greater thermal recoil acceleration as they are much lighter as well. While mass plays a role in the re-emission process, the surface area of an asteroid clearly explains why smaller asteroids experience a greater semi-major axis drift than larger asteroids. As shown, although the Yarkovsky effect is more pronounced on smaller asteroids, physical properties such as bulk density and thermal inertia may also affect its ability to emit radiation. Table 4 presents the asteroid Bennu with the highest SNR = 194.6. This provides the strongest signal for the Yarkovsky effect with the least relative noise, meaning that it is the most reliable, which could be because Bennu is much closer to Earth than most asteroids. Bennu is expected to make a close flyby in the year 2182, and there is a 0.05% chance of Bennu colliding with the Earth.[13] This probability validates that the Sun's thermal radiation can indeed influence Bennu's semi-major axis, with an uncertainty that may result in a dangerous collision with the Earth.

Figure 6: Asteroid (101955) Bennu's bulk density and thermal inertia.[14]



While Bennu provides data on bulk density and thermal inertia, it is important to recognize that other asteroids may exhibit different physical properties that may deviate from the trends of Bennu, which means that the Yarkovsky effect may manifest differently in other asteroids. Nevertheless, the theoretical assumptions and equations for each asteroid should have similar trends. The dashed curve represents the various levels of Bennu

[13] Ariana Garcia, "NASA gets ready for asteroid big as Empire State Building to hit Earth."
[14] David Vokrouhlický et al., "The Yarkovsky and YORP Effects," 14.

samples' bulk density and their thermal inertia, assuming that the surface of Bennu is smooth. The solid line accounts for the levels of roughness and bumps of the asteroid. The gray area is the uncertainty when measuring the roughness of the surface. At the peak of the bulk density, the Yarkovsky effect obtains its maximum effectiveness where thermal radiation from sunlight causes the most change in the semi-major axis.[15] However, the graph shows that rightwards from the peak, there is an inverse relationship between bulk density and thermal inertia, which is typically expected to be the reverse based on $I = \sqrt{k\rho c}$ where $I^2 \propto \rho$. As thermal inertia increases, bulk density should increase, however, the inverse may have occurred because of inconsistencies and variations in specific heat capacity or thermal conductivity that may affect the lower bulk density values in the equation. Regardless, there are other complex variables, specific heat capacity or thermal conductivity, that may significantly affect an asteroid's ability to resist and re-radiate photons. To more precisely determine how thermal inertia relates to the Yarkovsky effect and the Sun's thermal radiation, thermal inertia can be isolated with three formulas.

Thermal inertia and specific heat capacity formula:

$$I = \sqrt{k\rho c}$$

$$Q = mc\Delta T$$

$$I^2 \propto c$$

$$c \propto \frac{1}{\Delta T}$$

$$I^2 \propto \frac{1}{\Delta T}$$

Stefan-Boltzmann formula using differentiation:[16]

[15] David Vokrouhlický et al., "The Yarkovsky and YORP Effects," 14.
[16] *StudyPug*, "How to Approximate Derivatives from Tables: A Comprehensive Guide."

$$E = \sigma T^4$$

$$\frac{\delta E}{\delta T} = 4\sigma T^3$$

$$\frac{\Delta E}{\Delta T} \approx 4\sigma T^3$$

$$\Delta E \approx 4\sigma T^3 \Delta T$$

Finding the relationship between ΔE, I^2 and ΔT:

$$\Delta E \propto T^3 \Delta T$$

$$\Delta T \propto \frac{1}{I^2}$$

$$\Delta E \propto \frac{1}{I^2}$$

Treating asteroids as blackbodies, their re-emitted thermal radiation can be represented as radiant heat energy (E).[17] The equation provides an inverse relationship between the square of thermal inertia and the change in radiant heat energy A small difference in an asteroid's thermal inertia can quadratically affect the amount of thermal radiation re-emitted by an asteroid. The reason for this could be because when an asteroid's thermal inertia increases, its ability to store temperature is much higher; there will be a lower amount of radiation re-emitted as the process of re-emission would be slower, and thus a lower semi-major axis drift. The interplay between thermal inertia and thermal radiation provides evidence for the Yarkovsky effect, which allows an understanding of thermal forces and how they can alter an asteroid's orbital shape based on its composition. Specifically, when a force is applied on an asteroid such as thermal radiation, momentum must be conserved unless external forces act on it. Not only do the surface area and mass of asteroids affect the semi-major axis; but with the asteroids' bulk density and thermal inertia, their ability to absorb and redistribute this momentum based on the Sun's thermal radiation is also significant.

[17] Rahul Awati, "Stefan-Boltzmann constant."

As shown with the relationship between thermal inertia and change in radiant heat energy, thermal inertia must be accounted for when measuring the Yarkovsky effect. Therefore, asteroids with higher thermal inertia must maintain their surface temperature longer, conserving momentum more efficiently, and vice versa. This allows a clear observation of quantitative changes in these asteroids' orbits that match Yarkovsky effect predictions that smaller asteroids in orbit exhibit more obvious changes

4.3. UNDERSTANDING SEMI-MAJOR AXIS DRIFT RATE

Figure 7: 210 simulated Koronis family members via the Yarkovsky effect.[18]

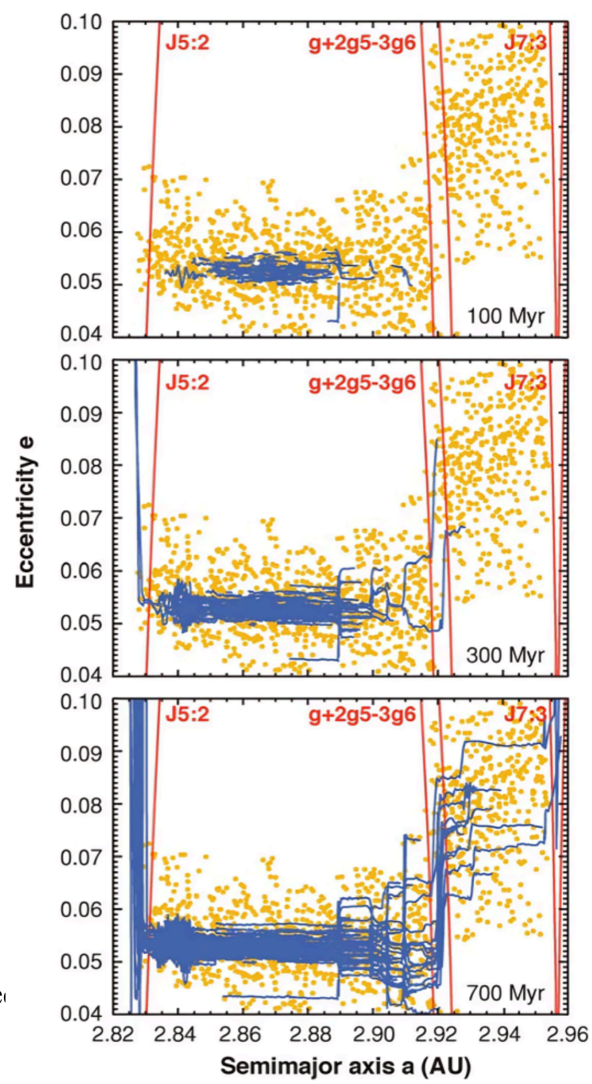


Figure 7 illustrates the existence of the Yarkovsky effect through the Koronis family of asteroids as a well-studied group that shares common physical and orbital properties. They are ideal for investigating the phenomenon as they are smaller asteroids that would, according to theory, experience greater semi-major axis drift with the Sun's force. Furthermore, because they reside in a stable region of the Main Asteroid Belt, it minimizes the effect of gravitational perturbations, which can reduce the amount of noise and increase the SNR, to clearly examine the effect of thermal radiation without significant

[18] William Bottke, "The Yarkovsky and YORP Effe

interference. With this, Figure 7 plots changes in the semi-major axis and eccentricity Koronis asteroid orbits at three different times: 100 million years (Myr), 300 Myr, and 700 Myr. The yellow dots represent the initial positions of the asteroids at the time of detection. The blue lines represent asteroids' orbital paths as they evolve through each of the three stages of time. The red vertical lines mark resonances where asteroids become affected by Jupiter's gravity as the asteroids are in the Main Asteroid Belt. J5:2 resonance demonstrates an asteroid that completes five orbits around the Sun while Jupiter completes two; J7:3 demonstrates another gravitational interaction where Jupiter completes three orbits as the asteroid completes seven; g+2g5-3g6 represents a more complex resonance involving Jupiter's gravitational influence. These resonances amplify orbital changes due to the significant gravitational force from Jupiter, which results in the "jumps" in an asteroid's eccentricity demonstrated in the blue lines. Nevertheless, the middle blue lines show the asteroids' semi-major axis drifting over hundreds of millions of years outside of Jupiter's gravitational resonances. This implies that even in the absence of Jupiter's gravitational force, the Sun's thermal radiation independently changes the orbital shape of asteroids validating the existence of the Yarkovsky effect. The Yarkovsky effect causes asteroids to slowly drift in the semi-major axis moving them left or right across the x-axis, with the blue lines showing asteroids' orbital eccentricity and semi-major axis expanding or shrinking due to thermal radiation after millions of years. The graph provides clear evidence of the Yarkovsky effect with the asteroids' orbital properties. Although they encounter resonances from Jupiter's force, before the gravitational interaction, it is shown that asteroids are moving in the Main Asteroid Belt with little gravitational force. By not accounting for Jupiter and the Sun's gravitational perturbations, it makes the detections more pronounced and reliable with less noise, clearly demonstrating that the Sun's thermal radiation is truly influencing asteroids' orbital path.

5. CONCLUSION

To conclude, sunlight is made up of photons which carry momentum and can push to change asteroids' course of direction. When photons reach the asteroid they can be reflected or absorbed. If photons are absorbed, asteroid surfaces can re-emit the photons which acts as a force that can propel asteroids and change their semi-major axis. It is essential to broaden the understanding of the implications of these findings on asteroid orbits to prevent potential hazards to Earth. The findings, such as Bennu's reliable data from probes and experimentation, represent strong evidence for the existence of the Yarkovsky effect and how the semi-major axis drift rate is due to the Sun's radiation for smaller asteroids. The effect pans out over millions of years, however, it is crucial to be aware of these forces for planetary defense systems and to plan for future risks. With these detections, although many have strong SNR values, there were many non-conclusive and invalid data points. Therefore, better-developed and improved models or probes should be used in the future to minimize the noise. These errors may be present due to the inconsistent rough surfaces and gravitational perturbations that may disturb the asteroids re-radiating photons. Instead of relying on observations from photometry and infrared spectra, to filter the noise, scientists can follow the experimentation process similar to NASA's OSIRIS-Rex, as it takes samples and observations closer to the asteroids. This can help increase SNR values for more reliable detections. Consequently, there can be many more improvements in the computational modelling of asteroids to help predict the Yarkovsky effect more precisely. For instance, sending probes on particular asteroids that have different attributes will expand the research not only for Bennu but also for other asteroids. The astrometric data gathered for the purpose of the Yarkovsky effect are useful in determining how gravity and thermal radiation affect asteroids.

However, there are better observation techniques that can provide insight into the reflective and emissive phenomena of the Yarkovsky effect, which can inform scientists more about the asteroid's re-emission of photons as an opposing force. Whether the asteroids' physical and orbital properties validate the existence of the Yarkovsky effect depends on numerous variables that are affected by sunlight-induced thermal radiation, but not by gravitational forces. This phenomenon is best represented by the semi-major axis drift rate which is attributed to the Sun's radiation; the effect primarily relates to an asteroid's diameter, surface area, mass, bulk density, and thermal inertia. Altogether, the valid detections proven by the high SNR and S values highlight the prevalence of this effect and that gravity is not the only force that affects an asteroid's motion; thermal radiation from the Sun, although a small force, is also a significant contributor to the trajectory of smaller asteroids.

Bibliography

Awati, Rahul. “Stefan-Boltzmann constant.” *TechTarget*. https://www.techtarget.com/whatis/definition/Stefan-Boltzmann-constant

Bassi, Margherita. “James Webb Telescope Confirms the Universe Is Expanding Faster Than We Thought—and Scientists Still Don’t Know Why.” *Smithsonian*, 2024. https://www.smithsonianmag.com/smart-news/james-webb-telescope-confirms-the-universe-is-expanding-faster-than-we-thought-and-scientists-still-dont-know-why-180985622

Bottke, William et al. “The Yarkovsky and YORP Effects: Implications for Asteroid Dynamics.” *CalTech*, 2006. https://kiss.caltech.edu/workshops/csc2011/references/yarkovsky-effect/The%20Yorkovsky%20and%20YORP%20Effects_Implications%20to%20Asteroid%20Dynamics.pdf

Dziadura, Karolina et al. “The Yarkovsky effect and bulk density of near-Earth asteroids from Gaia DR3.” *Astronomy & Astrophysics*. https://doi.org/10.1051/0004-6361/202347342

Garcia, Ariana. “NASA gets ready for asteroid big as Empire State Building to hit Earth.” *CHRON*. https://www.chron.com/news/space/article/nasa-asteroid-bennu-19362704.php

Geeks for Geeks. “Signal to Noise Ratio Formula.” 2024. https://www.geeksforgeeks.org/signal-to-noise-ratio-formula

Google. *Google Docs*, 2024. https://www.google.com/docs/about

Google. *Google Sheets*, 2024. https://www.google.com/sheets/about

Hyland, David et al. “NEA Mitigation via the Yarkovsky Effect.” *Research Gate*, 2013. https://www.researchgate.net/publication/269929507_NEA_mitigation_via_the_Yarkovsky_effect

Jet Propulsion Laboratory. “NASA Spacecraft Provides Insight into Asteroid Bennu’s Future Orbit.” *NASA*, 2021. https://www.jpl.nasa.gov/news/nasa-spacecraft-provides-insight-into-asteroid-bennus-future-orbit

Mohanta, Nihar, and Meena Murmu. “Bulk Density.” *ScienceDirect*, 2022. https://www.sciencedirect.com/topics/engineering/bulk-density

Study Pug. “How to Approximate Derivatives from Tables: A Comprehensive Guide.” https://www.studypug.com/calculus-help/estimating-derivatives-from-a-table

Vokrouhlický, David et al. “The Yarkovsky and YORP Effects.” *Cornell University*. https://arxiv.org/pdf/1502.01249

Appendix

Full list of valid Yarkovsky effect detections as of December 2014.

Object	**D (m)**	**da/dt ($\times 10^{-4}$ auMy^{-1})**	**SNR**	**S**
101955 Bennu	493	-18.95 ± 0.10	194.6	1
2340 Hathor	210	-17.38 ± 0.70	24.9	0.3
152563 1992 BF	510	-11.82 ± 0.56	21	0.6
2009 BD	4	-489 ± 35	13.9	0.2
2005 ES70	61	-68.9 ± 7.9	8.7	0.3
4179 Toutatis	2800	-3.75 ± 0.45	8.4	1.1
2062 Aten	1300	-6.60 ± 0.80	8.3	0.9
1999 MN	175	54.6 ± 6.8	8.1	0.5
6489 Golevka	280	-4.52 ± 0.60	7.5	0.1
1862 Apollo	1400	-1.58 ± 0.24	6.5	0.2
2006 CT	119	-47.6 ± 7.7	6.2	0.6
3908 Nyx	1000	9.6 ± 1.7	5.8	1.1
2000 PN8	130	49.3 ± 8.7	5.7	0.7
162004 1991 VE	827	19.2 ± 3.6	5.3	0.9
10302 1989 ML	248	38.7 ± 7.5	5.2	1.1
2100 Ra-Shalom	2240	-5.8 ± 1.2	4.7	1
29075 1950 DA	1300	-2.70 ± 0.57	4.7	0.6
85953 1999 FK21	590	-11.0 ± 2.4	4.5	0.3
363505 2003 UC20	765	-4.5 ± 1.0	4.5	0.3
2004 KH17	197	-42.0 ± 9.8	4.3	0.6
66400 1999 LT7	411	-35.0 ± 8.3	4.2	0.9
1995 CR	100	-314 ± 76	4.2	0.8
4034 Vishnu	420	-31.8 ± 8.0	4	1.2
85774 1998 UT18	900	-2.45 ± 0.63	3.9	0.2
1994 XL1	231	-37.6 ± 9.8	3.8	0.5
3361 Orpheus	348	6.2 ± 1.7	3.8	0.2
377097 2002 WQ4	422	-9.6 ± 2.6	3.7	0.4
138852 2000 WN10	328	17.7 ± 4.9	3.6	0.6
399308 1999 GD	180	47 ± 13	3.5	0.9
4581 Asclepius	242	-19.7 ± 5.7	3.5	0.4
2007 TF68	100	-60 ± 18	3.4	0.7
1999 FA	300	-43 ± 13	3.3	1.4
2063 Bacchus	1200	-6.6 ± 2.0	3.2	0.8
350462 1998 KG3	125	-25.2 ± 7.9	3.2	0.4
256004 2006 UP	85	-67 ± 21	3.1	0.7
37655 Illapa	950	-10.3 ± 3.5	3	0.5