A BODY SOLAR SAIL CONCEPT FOR THE DEFLECTION OF 99942 APOPHIS

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ABSTRACT

A novel concept for the mitigation of an asteroid impact with the Earth was developed for the Space Generation Advisory Council's 2008 "Move an Asteroid" technical paper competition. A body solar sail is shown to augment the solar radiation pressure on asteroid 99942 Apophis, deflecting it from its 2029 keyhole and reducing its 2036 impact probability to 1 in 1 million. An innovative wound film concept is presented and development and optimisation areas are discussed.

Keywords: 99942 Apophis, asteroid mitigation, solar sail, radiation pressure

NOMENCLATURE

a	Semimajor axis, m
A_{exp}	Area exposed to solar radiation pressure, m^2
AU	Astronomical Unit, 150 million km
C_R	Coefficient of reflectivity
d	Sidereal day, 86164 s
F_S	Force due to solar radiation pressure, N
G	Universal gravitational constant, 6.67428e-11 $m^3kg^{-1}s^{-2}$
h	Hour, 3600 s
IAC	International Astronautical Congress
m	Asteroid mass, kg
M_{Sun}	Solar mass, 1.9891e30 kg
Mt TNT	Megaton TNT, 4.184e15 J
n	Orbital frequency, $2\pi/T$ s^{-1}
NEA	Near Earth Asteroid
NEO	Near Earth Object
PET	Polyethylene terephthalate
p_s	Force per unit area due to solar radiation pressure, N/m^2
R_E	Earth Radius (equatorial), 6378 km
r_S	Radial unit vector between object and Sun
s	Second
SGAC	Space Generation Advisory Council
t	Time exposed to solar radiation, s
T	Orbital period, s
TNT	Trinitrotoluene
V	Object speed, m/s
y	Year, 365.25 days
γ_S	Acceleration due to solar radiation pressure, ms^{-2}
Δr	Displacement relative to prediction, m
ΔV	Change in velocity, m/s
μ	Gravitational parameter, GM km^3s^{-2}

INTRODUCTION

The Space Generation Advisory Council (SGAC) is a non-governmental ogranisation representing youth to the United Nations Programme on Space Applications [1]. In 2008 the SGAC initiated an international technical paper competition for students and young professionals with the goal of encouraging youth interest in innovative yet practical concepts for asteroid or comet mitigation. Participants are required to develop an original, technical solution for the deflection of an asteroid or comet with a diameter larger than 140 m.

The near Earth approach of the 330 m diameter asteroid 99942 Apophis on April 13, 2029 was selected for mitigation in this study. On this date, Apophis will pass close to the Earth at a distance of 38000 +/- 11700 km [2].

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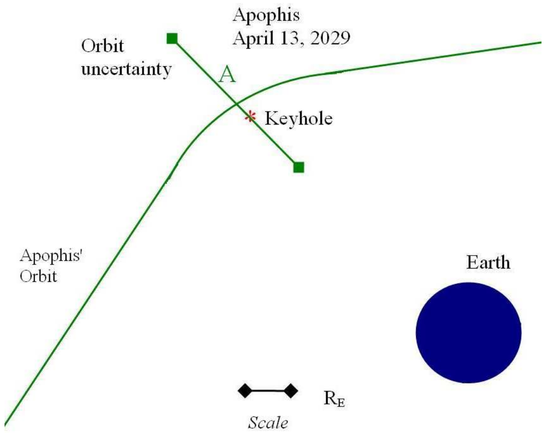

Fig. 1: Perturbation of the Orbit of Apophis Following its 2029 Encounter with the Earth's Gravitational Field

The gravitational field of the Earth generates a "keyhole" – a region in space through which a passing asteroid gains sufficient energy to cause its orbit to resonate. This phenomenon is also responsible for the occasional delivery of main belt asteroids into the inner solar system [5].

The 2029 keyhole for Apophis is just 600 m across and is located at a distance of 36550 km from the Earth. This is well within the orbit uncertainty for Apophis' 2029 pass, as shown in Figure 1. If Apophis passes through the keyhole in 2029, its orbit will commence resonance with a 7/6 frequency. This will result in Apophis and the Earth returning to the same place six revolutions (Apophis) and seven years (Earth) later, on April 13, 2036 [3], with an impact probability of 1 in 45000 [4]. An impact of Apophis with the Earth would be a sub-global event, causing 500000 fatalities [2] and releasing energy equivalent to approximately 880 Mt TNT [6].

Several mitigation techniques for both impulsive and slow push concepts are presently being developed. Impulsive concepts include the use of nuclear explosives (subsurface, surface or standoff), conventional explosives (subsurface or surface) and kinetic impact. Slow push concepts include the gravity tractor, mass driver, enhanced Yarkovsky, focused solar, solar sail, pulsed laser and space tug [2]. Although the technology readiness levels and immediate effectiveness of the slow push techniques are currently low, the typical decades-long impact warning time enables their further development.

The action period for Apophis is approximately two decades, thereby permitting the investigation of slow push mitigation concepts. The mitigation concept chosen for investigation in this study is solar radiation pressure as it is can generate the necessary thrust over a decade in deep space to deflect Apophis away from the 2029 keyhole.

Apophis

Apophis is a 330 m diameter near-Earth asteroid predicted to have several close encounters with the Earth over the next century. It is member of the Aten asteroid class, having a semi-major axis under 1 AU and crossing the Earth's orbit [2]. Its orbit causes it to spend much of its time on the opposite side of the Sun to the Earth, making it difficult to observe from the Earth. The next observation opportunity arises in 2011-2013.

Following its 2029 approach and interaction with the Earth's gravitational field, the orbit of Apophis is predicted to shift from the Aten to Apollo class. As shown in Figure 2, Apophis' post-2029 orbit will have a semi-major axis greater than 1 AU [7]. The energy received by Apophis in its 2029 encounter with the Earth's gravitational field results in an increase in its velocity relative to the Sun. The momentum required to deflect Apophis after 2029 increases by 5 orders of magnitude [8], hence it is advantageous to deflect Apophis prior to 2029.

Limited observations of Apophis have resulted in a restricted knowledge of its composition, shape, surface properties, internal structure and spin axis. This limited knowledge severely hampers the investigation of both impulsive and slow push mitigation concepts.
The known properties of Apophis are listed in Table 1.

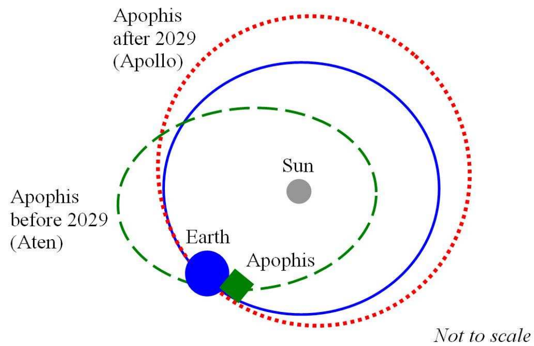

Fig. 2: Perturbation of the Orbit of Apophis Following its 2029 Encounter with the Earth's Gravitational Field

Characteristic	Value	Unit
Diameter	330	m
Mass	4.6e10	kg
Semimajor axis, a	0.922	AU
Eccentricity, e	0.191	
Inclination, i	3.331	deg
Ascending node, Ω	204.466	deg
Argument of perihelion, ω	126.364	deg
Mean anomaly, M	111.000	deg
Pericentre, r_p	0.746	AU
Apocentre, r_a	1.099	AU
Asteroid class	Aten	
Rotational period	30.5	h
Revolution period	325.6	d
Orbital speed (av.)	30.728	km/s
Escape velocity	0.14	m/s
Albedo	0.33	
Shape	Unknown	
Spin axis	Unknown	
Composition		
Bulk density (estimate)	2000	kg/m^3

Table 1: Characteristics of 99942 Apophis [2, 6, 10]

Deflection Scenario for Apophis Prior to 2029		
Design Point 1		
Action time	10	y
Momentum change	2.3e8	kgm/s
Velocity change	5	mm/s
Required thrust	0.731	N
Design orbit uncertainty	6378	km
Improvement from current orbit uncertainty	minimal	
Impact probability	1e-6	
Design Point 2		
Action time	6	y
Momentum change	1.2e6	kgm/s
Velocity change	0.026	mm/s
Required thrust	0.0056	N
Design orbit uncertainty	5	km
Improvement from current orbit uncertainty	very high	
Impact probability	1e-6	

Table 2: NASA Design Points for the Deflection of Apophis Prior to 2029

Apophis Design Points

In its 2006 deflection study [2], NASA created two design points for the deflection of Apophis prior to 2029. The deflection of Apophis at this time is such that both the keyhole and the Earth are avoided.

The first design point requires a relatively large change in velocity acting over a long period due to a high orbit uncertainty. The second design point requires a smaller velocity change over a shorter period due to an extremely low orbit uncertainty. These design points are described in Table 2 and are utilised in this study as benchmarks for the body solar sail concept.

DEFLECTION BY SOLAR RADIATION PRESSURE

The "body" solar sail concept involves the use of a coating over the surface of an asteroid to increase its reflectivity, enabling deflection by solar radiation pressure. Unlike for a solar sail, the body solar sail concept does not require knowledge of the spin axis to function. Thus no complex tether or long-term attitude control systems are necessary as the solar sail is coated on the body itself. The thrust generated from the enhanced solar radiation pressure always acts radially (away from the Sun), regardless of the spin orientation of the asteroid. Hence the body solar sail deflects an asteroid by steadily increasing its semimajor axis.

Assuming a spherical body, the force due to solar radiation pressure is

$$\vec{F}_S = -p_s C_R A_{\exp} \vec{r}_S \tag{1}$$

The perturbation acceleration due to solar radiation pressure is

$$\vec{\gamma}_S = \frac{\vec{F}_S}{m} \tag{2}$$

The change in semimajor axis due to a perturbation is given by the first Gauss equation [9]

$$\frac{da}{dt} = \frac{2}{n^2 a} V \gamma_S \tag{3}$$

Assuming that the solar radiation pressure causes a linear change in the semimajor axis and neglecting minor displacements in the remaining orbital elements, the displacement relative to prediction due to solar radiation pressure is given by [10]

$$\Delta r \approx -\frac{3}{2}\mu^{1/2}a^{-3/2}\frac{da}{dt}\left(\Delta t\right)^2 \quad (4)$$

The corresponding velocity change is given by

$$\Delta V = \gamma_s \Delta t \quad (5)$$

The solar radiation perturbation conditions for a range of reflectivity coefficients for design points 1 and 2 are given in Tables 3 and 4. Perturbations due to the solar wind, Yarkovsky and YORP effects are not considered in this study.

The ΔV requirement of design point 1 (5 mm/s) is achieved only with a reflectivity coefficient above 0.98. This is theoretically achievable with aluminised PET film, which has a reflectivity coefficient of up to 0.99 [6]. However, practical considerations such as film deposition and material degradation limit the achievable modified reflectivity coefficient. Design point 1 is therefore considered unattainable using the solar radiation pressure and is not considered further in this study.

The ΔV requirement of design point 2 (0.026 mm/s) is achieved with all modified reflectivity coefficients. Accounting for practical considerations such as actual exposed area, film deposition and surface coverage, and material degradation in deep space, design point 2 is considered attainable and is the focus of the remainder of this study.

C_R	F_S (N)	γ_S (m/s^2)	$\|\Delta r\|$ (10^3 km)	ΔV (mm/s)
0.30	0.22	4.9e-12	1.3	1.5
0.60	0.45	9.7e-12	2.6	3.1
0.80	0.60	1.3e-11	3.4	4.1
0.90	0.67	1.5e-11	3.8	4.6
0.95	0.71	1.5e-11	4.1	4.8
0.99	0.74	1.6e-11	4.2	5.1
1.0	0.75	1.6e-11	4.3	5.1

Table 3: Solar Radiation Perturbation Conditions with Reflectivity Coefficient for Apophis Design Point 1

C_R	F_S (N)	γ_S (m/s^2)	$\|\Delta r\|$ (10^3 km)	ΔV (mm/s)
0.30	0.22	4.9e-12	0.46	0.92
0.60	0.45	9.7e-12	0.92	1.8
0.80	0.60	1.3e-11	1.2	2.4
0.90	0.67	1.5e-11	1.4	2.8
0.95	0.71	1.5e-11	1.5	2.9
0.99	0.74	1.6e-11	1.5	3.0
1.0	0.75	1.6e-11	1.5	3.1

Table 4: Solar Radiation Perturbation Conditions with Reflectivity Coefficient for Apophis Design Point 2

WOUND FILM COATING

Coating concepts for altering an asteroid's surface properties include painting, application of powder and wrapping in a reflective film [6]. Painting and the application of powder present difficulties in even deposition over an extremely large surface area, deposition and adherence in a vacuum, adherence to a rapidly spinning body, and reduced performance in crevasses. Wrapping an asteroid in a reflective film eliminates all but the first of these difficulties.

Wound Film Concept

An innovative "wound film" coating concept utilising an orbiting spacecraft and the rotation of Apophis to deposit a layer of reflective film onto the surface is presented in Figure 3.

A spacecraft in orbit around Apophis accurately observes and relays data on Apophis' surface structure, spin and composition properties to Earth (a). The spacecraft manoeuvres itself into an orbit suitable for winding film onto the surface.
When a satisfactory starting location and orbit is found, a tether coupled to the start of the reflective film sheet is released from the spacecraft (b).
Once the film sheet reaches the surface, securing devices at the start of the sheet are anchored into the surface (c).
The tether is then slackened to avoid tearing the film over any rough surfaces (d).
Both the spacecraft's orbit and the rotation of Apophis are utilised in winding the film onto Apophis' surface (e).
Once the end of the film reaches the surface, it is anchored with securing devices (f).
The tether is disconnected from the film and wound into the orbiting spacecraft (g).
The spacecraft remains in orbit around Apophis and continues to observe and relay data on surface and spin conditions (h).

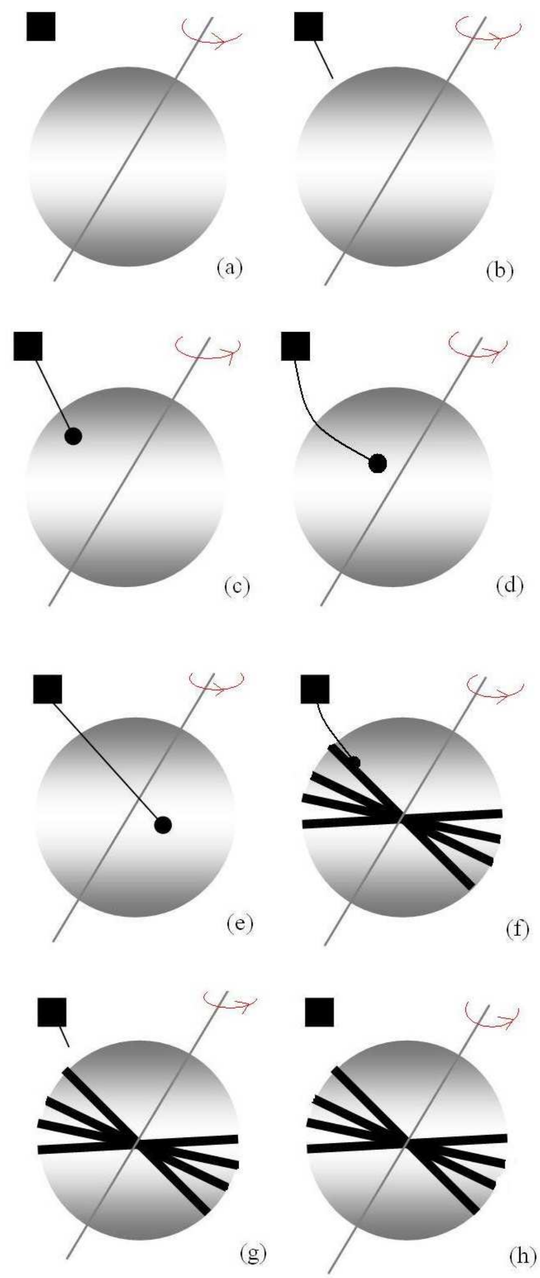

Fig. 3: Wound Film Reflective Film Coating Concept

Concept Evaluation

At present, no large-scale coating concept has ever been tested in space [6]. Although aluminised PET film exists and can be applied to this concept in its present-day form, suitable anchoring devices, tethers and space-rated winding machinery all require further development.

Due to Apophis' high rotational period of 30.5 hours, a securing device must be anchored sufficiently deep into the surface to prevent the ends of the film sheet flying off or being dragged along the surface. The highly remote nature of the mission calls for automated securing devices. Such a device may comprise pyrotechnically initiated bolts attached to reinforced portions of the film sheet.

A spacecraft designed to land gently on an asteroid and deploy a film sheet requires an extremely accurate knowledge of the asteroid's surface properties during the mission design stage, often several years prior to launch. This is not possible with current observational data, hence film deployment from an orbiting spacecraft utilising a guiding tether is conceived. In this way, observations of the asteroid's surface properties could be made whilst in orbit, ie during the mission itself. The tether is used as a guide to both feed and unfold the film sheet. Such a tether need not be longer than 100 m and can be fabricated from Kevlar. Tethers on smaller scales have been successfully tested in Earth orbit.

Both the orbit of the spacecraft and the rotation of the asteroid act to draw film from onboard the orbiting spacecraft. The winding machinery envisaged for this application must be lightweight, capable of functioning in microgravity and able to feed a long thin, folded film sheet over 1 km long and at least 1 m wide at speeds of the order of 150 mm/s for durations of up to several weeks. Exisiting software for fibre winding on contoured sections without slipping [11] would need to be developed to avoid a high tensile feed line that could destabilise the orbiting spacecraft.

Whilst the spin properties, shape and surface structure of Apophis are unknown at present, future detailed observations with ground-based radar and/or measurements from space-based equipment will provide this information.

Without knowledge of Apophis' shape and spin properties, an optimised winding pattern cannot be generated. Figure 4 shows some possible winding patterns. Future observations of Apophis and technological developments may reveal that full coverage is unnecessary and impractical. Coverage of the surface without entanglement may be achieved with a single film sheet or several film strips. Winding can also be conducted all at once or intermittently.

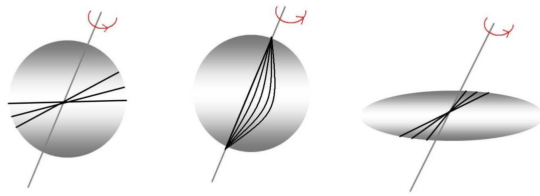

Fig. 4: Possible winding patterns
L-R: Slightly inclined orbit on a spherical asteroid; Polar orbit on a spherical asteroid; Polar orbit on a cylindrical asteroid.

This study assumed a spherical shape for Apophis, however a potato-shaped body is more likely, as shown in Figure 5. As further information on Apophis' shape becomes available, future studies may consider modelling Apophis as a cylinder of length 330 m and appropriate diameter.

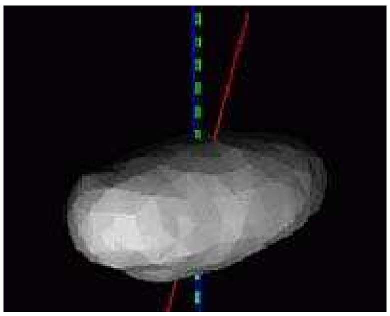

Fig. 5: Artist's Impression of Apophis Showing Axes of Geographical Centre (dotted) and Spin (solid) [12]

An estimated payload mass budget is given in Table 5. To achieve a 50% coverage of a 330 m diameter sphere with 13µm thick aluminised PET film [13], utilising lightweight winding machinery and securing devices with a 10 mm diameter, 100 m long Kevlar tether, the total payload mass required at Apophis is estimated to be 3850 kg.

Payload subsystem	Mass (kg)
Aluminised PET Film	3600
Winding machinery	150
Securing devices	50
Tether	50
Total payload	3850

Table 5: Estimated Payload Mass Budget

MISSION DESIGN

An estimated mass budget for the deflection scenario of Apophis prior to 2029 is given in Table 6. The launch vehicle selected is a Delta IV Heavy and is capable of launching a deliverable payload of 2200 kg to an Apophis-intercepting orbit from a single launch [2]. The wound film coating technique would therefore require 2 such launches.

Subsystem	Mass (kg)
Fuel	1900
Dry vehicle	5200
Structures and navigation	2964
Deliverable payload	2200
Total spacecraft	7064

Table 6: Estimated Spacecraft Mass Budget [2]

CONCLUSION

An innovative body solar sail asteroid mitigation concept utilising enhanced solar radiation pressure has been shown to be capable of deflecting Apophis prior to 2029 to reduce its 2036 impact probability to 1 in 1 million. An innovative wound film concept was presented for alteration of the reflectivity of Apophis, however more detailed observations are required in future for optimisation of the winding technique.

ACKNOWLEDGEMENTS

The author thanks R.G. Morgan for insightful discussions and reviews, A. Ridings for review of the manuscript, and D. Gildfind and T. Eichmann for support of this work.

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