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A3_1 Deflecting Asteroids using high-energy lasers

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Abstract

This article investigates the power of a laser needed to ablate the surface of the asteroid Apophis to produce a jet stream that will impart a force onto it, enough to deflect it from a direct trajectory to Earth. It is found that the power output needed is in the order of MW. The difficulty is in producing a laser beam with a very small divergence angle.

Introduction

One of the most important space challenges that could face human civilization is a large billion-kilogram asteroid colliding with Earth. We have already seen this happen in Earth's past, such as that which wiped out the dinosaurs and other forms of life 65 million years ago. NASA has so far registered 2000 rocks greater than 1000 m in diameter crossing Earth's orbit, and there may be more than 200,000 objects in the 10 m size range [1]. One such object which has caught people's attention is Apophis.

Apophis will make a close encounter with Earth in 2029 at a distance just above the geosynchronous satellites. We now know that there is a very small probability of a collision happening in 2029 [1], but if during this time it passes through a 'gravitational keyhole' [2] in space (a region of an orbit where a small gravitational input could cause a small body to collide with the large body it is orbiting), it might deviate onto a direct impact with Earth when it returns for another close encounter in 2036. Even then, there is still indeed a very small possibility of collision. Nevertheless the uncertainty still remains and we must be prepared if such a catastrophic collision were to occur.

We could either destroy the object or alter its trajectory. One such scenario envisions using lasers to divert the asteroid. In this case, the power of the lasers would ablate the surface of the asteroid, resulting in a vaporised outward jet stream which then imparts a thrust on the object according to Newton's Third Law. Here we investigate how much power a space- based laser must have to deflect the asteroid by more than one Earth radius.

Investigation

In principle the asteroid will behave like a rocket. We can then use Newton's Second Law in the form of a continuous variable mass, to calculate the force the jet stream with velocity v_{ex} has on the asteroid which is given as [3]:

$$F_{th} = \left|\frac{dM}{dt}\right| v_{ex} \ , \tag{1}$$

where $\left|{dM}/{dt}\right|$ is the rate at which mass flows out in the jet stream. The power output to deliver this thrust which we assume to be constant is then:

$$P = F \cdot v_{ex} = \left|\frac{dM}{dt}\right| v_{ex} \cdot v_{ex} \ . \tag{2}$$

Typical values of $\left|{dM}/{dt}\right|$ for a laser aimed at an exposed area of Apophis, is about 1 kg/s [1], thus:

$$P = F \cdot v_{ex} = v_{ex} \cdot v_{ex} = v_{ex}^2 \, . \tag{3}$$

If in 2029, Apophis manages to be deviated onto a direct trajectory to Earth, there is 7 years to veer off the asteroid a distance of at least one Earth radius. We now deduce a relationship between velocity of the jet stream and the time for Apophis to veer off one Earth radius. We do this by using the equation of motion:

$$s = ut + \frac{1}{2}at^2, \tag{4}$$

where u is the initial velocity (zero in this model), and a is the acceleration due to the thrust produced by the jet stream and is given as:

$$F = ma = F_{th} = \left|\frac{dM}{dt}\right| v_{ex} \quad , \qquad (5)$$

where F is the thrust on the asteroid which equals F_{th} due to Newton's Third Law and $\left|\frac{dM}{dt}\right|$ = 1kg/s in this model. Rearranging (5) then gives:

$$a = {}^{v_{ex}}\!/_{m} \quad ,$$

where m is the mass of Apophis given to be 2.7 $\times 10^{10}$ kg [4]. Substituting in the appropriate values into (4) and rearranging gives,

$$t = \frac{3.4\times10^{17}}{v_{ex}} \; . \qquad (6)$$

From (6) we clearly see that the greater the power output of the laser and hence the velocity of the jet stream, the shorter the time to deflect Apophis. We now find out how much power is needed to vaporise a small area of Apophis's surface, to produce this jet stream. This is given as [3],

$$P = \frac{dQ}{dt} = \frac{dM}{dt} c_p \, dT \quad , \qquad (7)$$

where dQ/dt is the rate of change of heat energy, dM/dt is taken to be again 1 kg/s, c_p is the specific heat capacity of the Asteroid's material given to be roughly about 600 J/kg/K [5] and dT is the temperature change of the material. The composition of Apophis has been determined and the temperature of vaporisation is given to be roughly about 2273 K [5]. From this we can calculate the power to vaporise the surface of Apophis to be about 1.36×10^6 W. Comparing this value with the expression in (2) we see that much more power is needed to vaporise the material than to give the jet stream a reasonable velocity to move Apophis.

The conceptual difficulty is in making a laser spot as small as the diameter of the asteroid at a far distance from it. A beam with aperture d and wavelength λ will have unavoidable divergence because of diffraction. The divergence angle is given as:

$$sin\theta = {}^{\lambda}\!/_{d} \quad . \qquad (8)$$

For typical values of a laser, $\lambda =$ 300 nm and $d =$ 5 mm [6], the divergence angle is 3.4×10^{-3} °. Using simple trigonometry we find that the maximum distance the laser must be from Apophis to make a spot that covers it, is 4.54$\times$ 10^6 m. We know Apophis's velocity is $\sim$30 km/s [4], giving a time of $\sim$151 s for the laser to deflect it one Earth radius. Looking at (6), we could just increase the velocity of the jet stream, but this means increasing the power output of the laser. These laser power outputs are non-existent today and this would contribute much more to the total laser power output than that needed to vaporise the material. In reality the laser would be near the asteroid and move with it, allowing a laser beam to be directed on to it for as long as it's needed or future technological breakthroughs could reduce the divergence angles.

Conclusion

We have seen here that the power to deflect the Asteroid depends very much on that needed to ablate the material. Increasing the power further will increase the velocity of the jet stream which in turn will reduce the time needed to deflect Apophis to a certain distance. In essence, the intensity of the laser must be sufficiently great, in the order of MW in power.

The problem is in producing a laser beam with a very small divergence angle so that it is able to concentrate on a small surface area and heat the material enough to vaporise it at a large distance. Another difficulty is in producing a laser beam that does not penetrate too deeply. This will simply heat the asteroid but won't produce any jet streams. We need a beam that penetrates just the right amount.

References

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