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P2_7 Close Encounters of the Unkind

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Abstract

Possible effects on satellites in Earth orbit caused by the unusually close encounter between the asteroid 9942 Apophis and Earth in 2029 are assessed. A worst case scenario for GPS, the most important system at risk, showed that the gravitational perturbation of orbits is negligible. Furthermore, it was found that Apophis will remain intact during the encounter, as its closest possible approach occurs at approximately twice the Roche limit.

Introduction

On the 13th of April 2029 the asteroid 9942 Apophis will have an extremely close encounter with the Earth, passing within the orbits of geostationary satellites [1]. Such near miss events involving asteroids of Apophis' size (with an estimated diameter of 270 m [2]) are thought to occur only every 800 years statistically [1]. First orbital measurements after its discovery indicated a collision with Earth was possible, but subsequent refinements showed that the closest approach will occur over the mid-Atlantic (42.9°W 29°N) at a distance from the centre of the Earth between 5.62 and 6.30 Earth radii [2]. While there is still some uncertainty about a small probability of impact in 2036 and later years, this article will assess the 2029 encounter and its possible effect on artificial satellites and the asteroid itself from gravitational and tidal forces.

A danger to GPS?

Apophis has a negligible probability of colliding with satellites: it will cross the equatorial plane of the Earth at an inclination of 40° [1], significantly before closest approach and is therefore no threat to the heavily populated geostationary belt above the equator. The large numbers of satellites in low Earth orbit have altitudes too low to be affected. However, the vital global positioning system (GPS) relies on a constellation of satellites orbiting at 55° inclination in a medium Earth orbit (MEO) with an orbital radius, *r*, of 26560 km (4.20 Earth radii) [3]. Therefore they could undergo a particularly close encounter and their orbits may be gravitationally perturbed. A full Keplerian model of the interaction is beyond the scope of this paper, hence only the ratio of gravitational forces on a satellite due to Earth, F_{ge}, and Apophis, F_{ga}, at closest approach is calculated. A worst case scenario is used, where a GPS satellite is directly below the asteroid at the moment of the encounter, where the latter is assumed to take place at the lower limit of 5.62 Earth radii. It is also assumed that the 2029 orbital configuration of the GPS system will be unchanged compared to today. The ratio is given by

$$\frac{F_{ge}}{F_{ga}} = \frac{Md^2}{m\,r^2}, \tag{1}$$

where M is the mass of the Earth, $5.97\text{x}10^{24}$ kg [4], r is as defined above and d is the closest approach distance between the satellite and Apophis, which is 1.42 Earth radii, the difference between 5.62 and 4.20 Earth radii. The mass of Apophis, m, along with its other physical parameters is not known precisely. In keeping with the worst case scenario, we use the upper limit of $6.49\text{x}10^{10}$ kg derived from the maximum size limit and maximum density (3400 kg m^{-3}) estimate given in [5]. Substituting these values into (1) shows that Earth's gravitational force on the asteroid amounts to $1.1\text{x}10^{13}$ F_{ga}. A noticeable orbital perturbation is therefore highly unlikely even for this worst case.

This result can be confirmed by calculating Apophis' Hill radius, r_h. The Hill radius provides a rough estimate for the extent of gravitational influence of a celestial body of mass m in orbit around a massive primary with mass M [6]. If a small body (i.e. a GPS satellite) entered the Hill sphere defined by r_h, its orbit would be drastically modified. It can be shown that

$$r_h = a(1-e)\left(\frac{m}{3M}\right)^{1/3}, \qquad (2)$$

where a is the semi-major axis, and e the eccentricity. For Apophis, these are currently 0.9223 AU and 0.191 respectively [7] and it is assumed no significant change will occur until 2029. Substituting the previously stated upper mass limit for m and the mass of the Sun, M, 1.989×10^{30} kg [8], into (2) gives a Hill radius of approximately 25 km. Therefore $r_h << d$, a significant gravitational interaction can be ruled out and the GPS system will not be at risk.

Asteroid survival

The second question to be addressed is whether Apophis itself is likely to remain intact during the encounter. Tidal disruption can be sufficient to break up small bodies approaching planetary gravitational wells – a notable event of this type was the disintegration of the comet Shoemaker-Levy 9 near Jupiter in 1992 [9]. The distance from the primary body (in our case Earth) at which tidal forces are equal to the secondary body's self-gravity is the Roche limit, given by

$$d_r = 2.44\,R\left(\frac{\rho_e}{\rho_a}\right)^{1/3}. \qquad (3)$$

R is the radius of the Earth, ρ_e is its density, ρ_a is that of the secondary (Apophis) and the numerical prefactor is obtained from the full derivation that accounts for the tidal deformation of the secondary into a spheroid [10]. If the secondary body comes within d_r of the centre of the primary, the tidal force will cause it to fragment. Using the previously quoted density estimate for ρ_a and a value of 5515 kg m^{-3} for ρ_e [4] gives a Roche limit of 18265 km, approximately one half of the closest approach distance d.

Conclusion

Although an unusually rare event, it has been shown that the 2029 encounter between Earth and Apophis will not have dramatic effects (beyond altering Apophis' orbit). Both manmade objects and the asteroid itself should survive, and it is likely that no repositioning of satellites will be required. To substantiate this conclusion, future work should be done on a full dynamical model (including important satellites) of the entire encounter.

References

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