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P1 5 Can we save Phobos?

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Abstract

This paper attempts to discover whether it is possible to save Mars' moon Phobos from ever crossing its Roche limit in many millions of years' time by using the most powerful rocket we have - SpaceX's Starship Super Heavy Booster - to push it into a wider circular orbit. We find that Starship has to deliver 1,499 ms^{-1} of delta-V to Phobos to push it into a place where it will never cross this Roche limit, but we also find that this takes a single booster 6,254 years to accomplish at full thrust.

Introduction

The planet Mars has two small potato-shaped moons in near-circular orbits around it. Phobos is the innermost and largest of the two, measuring roughly 13 km long, at a distance of 9,375 km [1] from Mars. It has been discovered that Phobos' orbit is slowly decaying and the tiny moon is spiralling inwards towards the planet. Recent observations have narrowed down this orbital decay rate to around 1.8 cm yr^{-1} [2] [3].

As Phobos slowly falls towards the Red Planet, it approaches the Roche limit d_R, which is the distance from the primary body - with a given radius R_p and density ρ_p - at which a secondary body with density ρ_m is destroyed due to tidal forces. For a completely rigid solid body, the Roche limit is expressed as [4],

$$d_R = R_p \sqrt[3]{\frac{2\rho_p}{\rho_m}}, \tag{1}$$

However, this equation does not take into account the rigidity of the rocks with which bodies are made. A version of this equation that assumes that a body is completely fluid is as follows [4],

$$d_R = 2.44 R_p \sqrt[3]{\frac{\rho_p}{\rho_m}} \tag{2}$$

Phobos' low density has led scientists to describe it as a "rubble pile" [5] - hence for the sake of simplicity, we will assume the true Roche limit lies exactly halfway between the perfectly solid and fluid values.

This paper attempts to find out whether human technology can save Phobos from ever crossing this Roche limit during the lifetime of the Solar System.

Tables 1 and 2 show information on the important parameters and characteristics of Mars and Phobos that will be used for calculation in this paper. [1] [6] [7] [8]

R_p(km)	M(kg)	ρ_p(kgm^{-3})
3390	$6.41\mathrm{x}10^{23}$	3933

Table 1: Martian parameters and characteristics.

In table 2, R_{orb} is the orbital radius of Phobos and T_{orb} is its orbital period.

R_{orb}(km)	M(kg)	ρ_m(kgm^{-3})	T_{orb}(s)
9375	1.06x10^{16}	1866	27540

Table 2: Phobos parameters and characteristics.

A good way to try and save Phobos with human technology is with rockets. The most powerful rocket ever created and launched, SpaceX's Starship Super Heavy Booster, unleashes a thrust of 80.51 MN [9] at full power. If this force is constantly applied exactly tangentially to Phobos' orbital path, its semi-major axis will increase, taking it further away from its Roche limit.

To calculate the difference in velocity needed to change Phobos' orbit by enough such that it never crosses the Roche limit during the lifetime of the Solar System, we need to consider Newton's Law of Gravitation, which shows that the orbital velocity of any object is [10]

$$v_{orb} = \sqrt{\frac{GM_p}{R_{orb}}}, \tag{3}$$

where G is the universal gravitational constant and M_p is the mass of the planet, in this case, Mars.

The remaining lifetime of the Sun has been roughly calculated by [11] to be 5.4 x 10^9 years.

Results

The d_R value calculated from eq. (1) was 5,476 km, and the value calculated from eq. (2) was 10,605 km. The value exactly between these is 8,040 km, which we will make the crude assumption to be the Roche limit.

The Sun will die in 5.4 billion years, and Phobos' orbital decay is 1.8 cm per year, so we find that Phobos will have to be at a distance of 105,240 km from Mars for this orbital decay to never take it inside the Roche limit during the Sun's lifetime. Using eq. 3, we find that the orbital velocity associated with this distance is 637 ms^{-1}. Phobos' current average orbital velocity is 2,136 ms^{-1} using this same equation, so Starship would have to deliver a delta-V of 1,499 ms^{-1} to Phobos to achieve this.

However, the acceleration produced by the Starship Super Heavy Booster thrust on Phobos, using Newton's 2nd Law, is calculated to be 7.6 x 10^{-9} ms^{-2}. This implies that a single Starship would have to burn for 6,254 years at full thrust in order to achieve this distance, which is equivalent to 7.16 x 10^6 Phobos orbits around Mars. So many orbits under a tangential force result in virtually no changes to its orbital eccentricity, so the orbit essentially remains circular.

Furthermore, Starship's fuel tank is not infinite, it contains 3,650 tonnes of fuel at full capacity [9], and it burns through that fuel at around 18,143 kg s^{-1} [12], resulting in a maximum burn time of only 201 s. So, to achieve this result, a single Starship has to burn through approximately 9.81 x 10^8 full fuel tanks. This is equivalent to 3.58 x 10^{15} kg of fuel, which is around 1/3 the mass of Phobos itself.

Discussion & Conclusion

Clearly, there are a lot of issues with this being at all feasible. A glaring one being that Starship has to burn for such a long time with a relatively small fuel tank. This could be solved by putting many more Starships to assist. 10 Starships would take 625 years, and 1000 Starships would take 6.25 years, etc. However, the mass of fuel required is still the same. Even if we had enough Starships to move its orbit out within a few days, the changes in eccentricity would become non-negligible, and Phobos' orbit would change a lot more chaotically.

All of this also fails to take into account that it would take a truly enormous rocket to even get a fully fuelled Starship over to Mars in the first place. We cannot lift a full Starship tank of fuel off the ground with another Starship.

Another issue with this is that Mars has another moon, Deimos, which orbits in a very similar inclination to Phobos. So it would obstruct Phobos going further outwards, resulting in either a close encounter which would scatter both of them, or a collision between the two.

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