Journal of Physics Special Topics
An undergraduate physics journal

P4 1 Luna Ring: A Hypothetical Outcome of a Major Asteroid Impact

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October 30, 2024

Abstract

In this article, we investigate the effects of a major asteroid collision with Earth's Moon, potentially forming a debris ring around Earth. By examining the tidal forces and the Roche limit, the study concludes that such an event is highly improbable since such a large asteroid would not have gone undetected and the collision would disintegrate the Moon on collision.

Introduction

In this paper, we discuss the likelihood of a debris ring forming around Earth, due to the Moon being knocked within the Roche limit by a near-Earth-object (NEO) and breaking apart forming a ring like those of Saturn.

Roche Limit

One of the most striking phenomena in a planetary system is that of planetary rings. The most common cause of their formation is moons passing the Roche limit. The Roche limit is the radius where tidal forces from the parent body overcome the Moon's gravity, breaking it apart. The resulting debris may eventually form a ring system. The radius at which this occurs depends on the mass of the parent body and the density of the satellite. Under the assumption that the Moon is hydro-static, Roche limit can be calculated by:[1]

$$R_r = 2.44\left(\frac{\rho_E}{\rho_m}\right)^{1/3} R_E \tag{1}$$

We used the values Earth's radius $R_E = 6371$ km, $\rho_E = 5515$ kgm^{-3} and $\rho_m = 3340$ kgm^{-3} for densities[2]. The subscript m and E are used throughout to represent the Moon and Earth. Assuming circular orbit, using Kepler's third law, the velocity of the orbit can be calculated.

$$T^2 = \frac{4\pi^2}{GM_E}R_r^3 \tag{2}$$

$$v_r = \sqrt{\frac{GM_E}{R_r}} \tag{3}$$

Where M_E is the mass of Earth (5.97×10^{24} kg). Assuming a single pulse orbital change path is taken. The velocity change needed to move the Moon within the Roche limit is:

$$\Delta v = v_r - v_c \tag{4}$$

Where $v_c = 1.022$km/s, the Moon's current average orbital velocity[2] and v_r is the orbital velocity at the Roche limit. We assume that the asteroid's momentum is fully transferred to the Moon to relate this velocity change to a single impact.

$$M_{ast}v_{ast} = (M_m + M_{ast})\Delta v \tag{5}$$

We rearrange Equation 5 to solve for the asteroid's mass.

$$M_{ast} = \frac{M_m \Delta v}{v_{ast} - \Delta v} \tag{6}$$

For this we used the average velocities of NEOs 19.3km/s. [3] The mass of the Moon, M_m can be seen in Table 1.

Binding limit

To further determine the likelihood of the Moon becoming a ring by passing the Roche limit, we must ascertain if the collision we calculated would not break the moon apart before its orbit decays. This requires a collision to have more energy than the binding energy of the Moon.

$$U_{grav} = \frac{3GM_m^2}{5R_m} \tag{7}$$

Where M_m is the Moon's mass as stated in Table 1 and R_m its radius = 1740 km[2] and G is the gravitational constant. To keep this in terms of mass, we equated this to the kinetic energy of an impact and rearranged for mass to get the relation. Using the same velocity as before.

$$M = \frac{6GM_m^2}{5R_m v_{ast}^2} \tag{8}$$

Results and Discussion

Moon	Mass (kg)
Ganymede	1.48×10^{23}
Titan	1.35×10^{23}
Callisto	1.08×10^{23}
Io	8.93×10^{22}
Luna	7.35×10^{22}
Europa	4.80×10^{22}
Roche limit	1.71×10^{22}
Binding limit	6.675×10^{20}

Table 1: Comparative masses of major moons and required mass for each limit

Table 1 presents the masses of the heaviest moons in the solar system, along with the hypothetical asteroid required for the Moon to pass the Roche and Binding limit. The mass of the hypothetical asteroid necessary for this collision, 1.71×10^{22} kg, ranks seventh on the list, it is heavier than all known asteroids and dwarf planets in the solar system. Notably, this mass is two orders of magnitude greater than the estimated mass of an asteroid, 6.675×10^{20} kg, that would disintegrate the Moon and likely form a ring.

Although not all near-Earth-objects are documented, it is likely that any NEO larger than Pluto would have been detected by now. Furthermore, the only known objects capable of causing such a collision are located in established orbits far from Luna, this suggests that the probability of such an impact occurring is extremely low unless there are significant disruptions to the current orbits within the solar system.

Conclusion

In conclusion, the likelihood of Luna becoming a planetary ring due to tidal forces is improbable. Furthermore, as the Moon continues to recede from Earth each year, this likelihood diminishes even further. A collision with an asteroid of enough mass would cause the Moon to break up upon impact before reaching the Roche limit.

References

[1] NASA. *Spacemath: Moon - Problem 5 Page 49*. `https://spacemath.gsfc.nasa.gov/moon/5Page49.pdf`. Accessed 28 September 2024. n.d.

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[3] J. S. Stuart and R. P. Binzel. "Bias-corrected population, size distribution, and impact hazard for the near-Earth objects". In: *Icarus* 170.2 (2004), pp. 295–311. ISSN: 0019-1035. URL: `https://doi.org/10.1016/j.icarus.2004.03.018`.