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P1 3 A Mistaken Man-Made Moon

J. Turner, C. Kirkham, E. Smith

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract

There are currently around 15,000 satellites orbiting Earth, along with tens of thousands of other man-made objects; the total mass of these objects is estimated to be around 14,700 tonnes. It is calculated that, even in a worst-case scenario of these objects accumulating near or on the surface of the Moon, the total disturbance in the Moon's orbital period would be 1.42×10^{-7} s. For a 1 second change in the orbital period, a total mass of 1.04×10^{14} kg would be required, 6 million times more mass than is currently orbiting the planet.

Introduction

Since 1957, humans have been sending satellites into Earth's orbit, with varying levels of success. Today, almost 15,000 satellites [1] are in orbit along with tens of thousands of pieces of space junk that contribute to orbital pollution. This paper explores the idea of whether the combined mass of all the man-made objects orbiting Earth would be sufficient to cause a disturbance in the Moon's orbit, and how the placement of this accumulation affects the magnitude of this disturbance.

Where Mass Matters Most

To maximise the potential of the mass at hand, the position where it converges needs to be accounted for. The first place to consider is if it is close to the Moon. For these calculations, we will simplify the situation by considering only the Moon, the Earth, and the third mass, ignoring the gravitational influence of any other nearby celestial bodies. The Moon, with mass M_M, experiences an acceleration due to the Earth with mass M_E at a distance d, and a secondary mass m at position $\vec{r}$. Gravitational acceleration of the Moon due to a point mass m follows the N-body formulation of Newtonian gravity [2]. For the case $m \ll M_E, M_M$, this simplifies the perturbation of gravitational acceleration to,

$$\vec{a}_{\text{pert}} \approx -\frac{Gm}{|\vec{d} - \vec{r}|^3}(\vec{d} - \vec{r}) \tag{1}$$

Using this equation, the perturbation in gravitational acceleration, $\vec{a}_{pert}$, increases as the distance between the mass and the Moon decreases, reaching a maximum at the surface of the Moon where $|\vec{d} - \vec{r}| = R_{\text{Moon}}$, where R_{Moon} is the radius of the Moon. This results the magnitude of the near-Moon gravitational perturbation,

$$a_{\text{near}} \approx \frac{Gm}{R^2_{\text{Moon}}} \tag{2}$$

Other notable points to consider could be the Lagrange points that naturally arise from the N-body acceleration equation. However, in a restricted three-body problem, a negligible mass placed at a Lagrange point would remain in equilibrium and have no effect on the orbit of the

Moon around the Earth. The final place to consider is on the opposite side of the Earth to the Moon (antipodal point). In this configuration $\vec{r}$ is equal to $-d$ and Equation 1 can be simplified to,

$$a_{\text{ant}} = \frac{Gm}{4d^2} \tag{3}$$

Where a_{ant} is the antipodal perturbation on the Moon. Taking the ratio of the near-Moon and antipodal perturbations to be,

$$\frac{a_{\text{ant}}}{a_{\text{near}}} \approx \frac{R_{\text{Moon}}^2}{4d^2} \tag{4}$$

It can be calculated using values $R_{\text{Moon}} = 1.74 \times 10^6$ m [3] and $d = 3.84 \times 10^8$ m [3], that the antipodal perturbation is $\sim$200,000 weaker than that of the near-Moon placement. These calculations suggest that the largest disturbance to the Moon's orbit would be created by accumulating the mass at, or near the lunar surface.

The Minimum Mass Metric

Using the near-Moon placement for the mass, is there enough mass orbiting Earth to cause a significant disturbance in the Moon's orbit?

Current space environment statistics from the European Space Agency estimate that the total mass of space objects in Earth orbit is approximately 1.47×10^7 kg [4]. Using this value as m in Equation 2, along with the gravitational constant G, and R_{Moon} as stated above, we can calculate $a_{\text{near}} = 3.24 \times 10^{-16}$ ms^{-2}. A change in orbital period can be calculated using the change in effective central mass felt by the Moon. The perturbing acceleration calculated can then be compared to the gravitational acceleration due to Earth,

$$a_{\text{near}} = \frac{Gm}{R_{\text{Moon}}^2} = \frac{G\Delta M_{\text{eff}}}{d^2} \tag{5}$$

Where ΔM_{eff} is the effective change in mass felt by the Moon, cancelling G and rearranging for ΔM_{eff} gives the relation,

$$\Delta M_{\text{eff}} \approx m \left(\frac{d}{R_{\text{Moon}}}\right)^2 \tag{6}$$

Evaluating this gives $\Delta M_{\text{eff}} = 7.16 \times 10^{11}$ kg, which can be used in Kepler's third law to find a change in orbital period,

$$T = 2\pi\sqrt{\frac{d^3}{GM_E}} \tag{7}$$

Taking logarithms of Equation 7 and differentiating both sides results in the equation that gives the relation,

$$\frac{dT}{T} = -\frac{1}{2}\frac{dM}{M_E} \tag{8}$$

Since ΔM_{eff} is negligible compared to the Moon's mass of 7.3×10^{22} kg [5], we can take it to be small and use it in place of dM to find the fractional change in the orbital period $\frac{dT}{T}$, and then rearrange to obtain the absolute change, dT. Using $T = 27.32166$ days [6] and other values as stated above yields an absolute value of $dT = 1.42 \times 10^{-7}$ s, a 6.02×10^{-12} % change in the Moon's current orbit and one that cannot be considered significant.

So if the combined mass of man-made objects orbiting Earth is not sufficient to cause a disturbance in the orbit of the Moon, how much mass is needed? Considering a 1-second change in the orbital period as significant, rearranging Equation 8 for dM and substituting that for ΔM_{eff} in Equation 6 yields a result of 1.04×10^{14} kg. A value a factor of $\sim 6 \times 10^6$ larger than the current total mass orbiting Earth.

Conclusion

There are tens of thousands of man-made objects orbiting Earth, making up almost 15,000 tonnes of material. However, even this much mass accumulated in a worst-case scenario on the surface of the Moon would still not affect its orbit around Earth to a significant level. The maximum change in orbital period, resulting from the effective change in mass it feels, is $dT = 1.42 \times 10^{-7}$ s. And the amount of mass needed to change the orbital period by 1 second was found to be 1.04×10^{14} kg, approximately 6 million times more massive than the total mass of man-made objects in orbit.

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