A Dialogue on Tidal Forces in the Manner of Galileo

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Proem

In which the philosopher Salviati instructs Sagredo and Simplicio concerning the relations of the Moon and the Sun and the curious fact that though the two appear of equal size, yet the lesser body rules the tides.

First Day: On the General Relation of Tides to Apparent Size

Sagredo. I have often heard that tides are a result of the Moon, and in lesser degree, the Sun. But as the two heavenly bodies seem the same in the heavens, why should one so greatly prevail over the other?

Simplicio. Surely because the Moon is nearer, its influence overwhelms the Sun's. And thus distance alone explains all.

Salviati. Your answer contains a portion of truth but not its whole. It is certain that the tidal force varies strongly with distance, but to understand this properly, we must compare three things: the body's mass, its distance, and its apparent breadth in the sky.

Let M be the body's mass, R its true radius, r its distance from Earth, and θ its angular diameter. Then for small angles,

$$\theta \approx \frac{2R}{r}.$$

And the strength of tide it raises varies as

$$a_{\text{tidal}} \propto \frac{M}{r^3}.$$

But since $M = \frac{4}{3}\pi R^3 \rho$, where ρ is its mean density, we may eliminate R and find the delightful result:

$$a_{\text{tidal}} \propto \rho\, \theta^3.$$

Sagredo. So the tidal power depends not only on how large the body appears, but also on how dense it is!

Salviati. Precisely so. If two bodies appear the same in the sky and have the same density, they would raise the same tides, regardless of their masses or distances in themselves.

Second Day: Application to Our Moon and the Sun

Sagredo. Let us test the principle on our own heavens.

Salviati. The Moon, being of rocky nature, has a mean density of about 3.34 g/cm^3, while the Sun, being a vast ball of rarefied fires, measures but 1.41 g/cm^3. Yet their disks in our firmament are almost equal to sight, a marvelous accident granting us the grace of eclipses. Hence,

$$\frac{a_{\text{Moon}}}{a_{\text{Sun}}} \approx \frac{\rho_{\text{Moon}}}{\rho_{\odot}} \approx 2.4,$$

so the lunar tide is more than twice as strong as the solar.

Simplicio. I had believed, following common instruction, that it was distance alone that furnished the explanation. But this introduces density as well, which had not been accounted.

Salviati. The dependence on $1/r^3$ is indeed correct, but only when comparing two bodies of the same size. When their apparent breadths are equal, the distance enters the tidal force implicitly through the density.

Third Day: On a Curious Objection Concerning Enlargement of the Moon

Simplicio. Permit me an objection. Imagine that we inflate the Moon until it equals the Sun in diameter, and place it at the same distance without altering its density. Its appearance would be unchanged—does its tidal rule stay or alter?

Salviati. A penetrating question! Since you have assumed its density remains that of the Moon and its apparent size remains equal to the Sun's, the expression

$$a_{\text{tidal}} \propto \rho\, \theta^3$$

tells us immediately: its tide would be nearly the same as our present Moon's, but somewhat greater than the Sun's—for the Moon's density is over twice that of the Sun.

Sagredo. So if a body grows but recedes proportionally, the eye sees no change and neither does the tide.

Salviati. Exactly so. Thus your imaginary giant Moon at the Sun's place would rule the seas almost as the real Moon does.

Final Reflections

Sagredo. Let us summarize: though the Moon and Sun seem equal to sight, their powers differ because their compositions differ; rocky Moon against airy Sun.

Salviati. You have grasped it. For tides depend on the cube of what we behold and the substance of what we do not. The Moon is denser; therefore it commands the ocean more strongly, despite being the lesser body in size.

Simplicio. I concede the correction. The simple rule of nearness lacked this subtlety, and without it the mind is deceived by appearances alone.

Epilogue

Thus in this discourse the gentlemen have discovered that Nature shapes her effects not merely by bodies' appearances, but by their hidden substance. And though the Sun and Moon stand alike in our heavens, yet the humble Moon rules our tides, not by size but by density.