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Additional Solar System Gravitational Anomalies

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Abstract: This article is motivated by uncertainty in experimental determinations of the gravitational constant, G, and numerous anomalies of up to 0.5 percent in Newtonian gravitational force on bodies within the solar system. The analysis sheds new light through six natural experiments within the solar system, which draw on published reports and astrophysical databases, and involve laboratory determinations of G, orbital dynamics of the planets and the moons of Earth and Mars, and non-gravitational acceleration (NGA) of 'Oumuamua and comets. In each case, values are known for all variables in Newton's Law $F = \frac{G \cdot M \cdot m}{R^2}$, except for the gravitational constant, G. Analyses determine the gravitational constant's observed value, $\hat{G}$, which—across the six settings—varies with the mass of the smaller, moving body, m, so that $\hat{G} = G \times (0.998 + 0.00016 \times \ln(m))$. While further work is required, this examination shows a scale-related Newtonian gravity effect at scales from benchtop to Solar System, which contributes to the understanding of symmetry in gravity and has possible implications for Newton's Laws, dark matter, and formation of structure in the universe.

Keywords: Newton's Law; gravitational anomalies; astrophysics; 'Oumuamua; comet NGA; standard model; symmetry in gravity

Citation: Coleman, L. Additional Solar System Gravitational Anomalies. *Symmetry* **2021**, *13*, 1696. https://doi.org/10.3390/sym13091696

Academic Editors: Maxim Yu. Khlopov and Pedro Pina Avelino

Received: 9 August 2021
Accepted: 13 September 2021
Published: 14 September 2021

1. Introduction

Astronomers rarely have the opportunity to handle or experiment on their subjects and so depend on remote observations, which—when compiled in databases—can offer rich insights. This analysis is motivated by gravitational anomalies that have been observed at the smallest and largest scale [1–4] and examines them using results from determinations of G and data on the velocity of planets and smaller bodies in the solar system.

One set of small-scale anomalies are seen in experimental determinations of the gravitational constant, G, which use masses of a few kg located within centimetres of each other. These experiments are drawn on by the International Astronomical Union to develop the official value of G, which is 6.6743×10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ [5]. Although determinations of G are notoriously complex, its official value has 0.01 percent uncertainty, which is orders of magnitude greater than that for other fundamental constants [6].

At a larger scale, anomalies reflect variation in solar gravitational mass, $GM_\odot$, of up to about 0.5 percent and are described as a missing mass problem and/or occurring at low accelerations [7]. An example involves 1I/2017 U1 'Oumuamua, which is the first macroscopic object to be observed that came from outside the solar system and had an unexplained non-Newtonian acceleration of 0.1 percent away from the Sun [8], so that—according to a NASA press release (number 18-056 of 28 June 2018)—it was 40,000 km further away when it disappeared from view than if only gravitational force had been acting.

This paper sheds new light on solar system gravitational anomalies through six natural experiments using data provided by others in published reports and astrophysical databases. These experiments test Newton's Law $F = \frac{G \cdot M \cdot m}{R^2}$, where all variables are known except G, which allows calculation of the observed value of the gravitational constant, $\hat{G}$. The experiments comprise:

- laboratory determinations of G by 13 teams using target masses up to 5 kg;

- orbital dynamics of the planets and of the moons of Earth and Mars, which assume Keplerian motion;
- non-gravitational acceleration (NGA) of 'Oumuamua and 70 comets.

The analysis compiles previous research and interprets it to identify a scale-related effect in natural experiments from benchtop to Solar System bodies that help explain gravity's lack of symmetry [9]. Gravity is the only force that breaks conformal or scale-independent symmetry, which is most obvious in the breakdown of Newtonian gravity as scale increases [10]. Because Newton's Law was considered reliable in the solar system, the scale effect in galaxies and distant stars was explained by the proposed existence of dark matter and dark energy. Thus evidence that the gravitational constant, G, is scale-dependent within the solar system opens the possibility of universal bias in laws of gravitation.

2. Solar System Gravitational Anomalies

This section draws on materials published by others and calculates an observed value of the gravitational constant, $\hat{G}$ that fits reported data. All data are referenced, but details of their determination are only provided where available.

2.1. Experimental Determinations of G

The value of the gravitational constant, G, is typically determined through benchtop experiments in controlled conditions that measure the interaction between a large mass that serves as the gravitational attractor and a smaller target mass [11,12].

Published estimates of G were identified through review articles [6,11,13–15] and a search using keywords. Table 1 provides details from 13 modern experiments that have attractor mass <550 kg, report G to at least four significant figures and provide details of the target mass.

There is a history of plotting experimentally derived values of G [16], and this is repeated in Figure 1. Regression results are reported in panel B of Table 1 and show a statistically significant, positive relationship ($p < 0.01$; t-statistic equals 2.06) that explains over a quarter of the cross-sectional variation in the observed gravitational constant, $\hat{G}$ (which is in units of $m^3 \cdot kg^{-1} \cdot s^{-2}$)

$$\hat{G} = \{6.674 + 0.00020 \times \ln(\text{Target mass})\} \times 10^{-11} \quad (1)$$

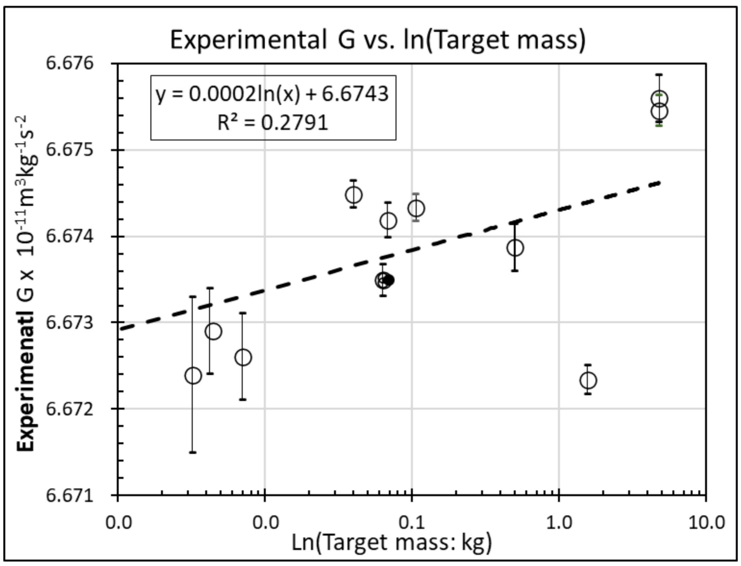

Figure 1. Relationship between $\hat{G}$ and target mass.

Lines 5 and 7 of Table 1 report $\hat{G}$ derived from twinned experiments by researchers at Huazhong University of Science and Technology (HUST), Wuhan, using a torsion pendulum with the time-of-swing method. Results from experiments by the same team using equipment that is the same except for target mass should minimise systematic and other errors. Researchers confirmed the results above with the finding that $\hat{G}$ rose from 6.67349 to 6.67418 $\times 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$ when the target mass rose from 63 to 68 g [17].

Benchtop determinations of G also vary the attractor mass and thus are natural experiments that test for a non-linear relationship between gravity and attractor mass, M. Unreported analysis followed a similar procedure to that above using data from experiments reported in Table 1 and a compilation of values of G and M [18]: neither showed any relationship. Nor was there a significant difference in G identified from twinned experiments by a team using 500 L tanks as attractor masses that were filled with water and mercury [19]. Thus there is no evidence of anything other than a linear relationship between force and attractor mass.

Table 1. Experimental results for benchtop determinations of G.

Panel A: Details of Published Studies				
Reference	**Apparatus**	**G ($\times 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$)**	**Attractor Mass (kg)**	**Target Mass (kg)**
[20]	Torsion balance	6.67387 ± 0.00027	54.00	0.5000
[21]	Torsion pendulum, time of swing	6.67400 ± 0.0007	20.98	0.0007
[22]	Torsion pendulum, time of swing	6.67239 ± 0.0009	12.50	0.0032
[23]	Torsion balance	6.6729 ± 0.0005	8.00	0.0044
[24]	Torsion pendulum, time of swing	6.674184 ± 0.000078	1.56	0.0680
[25]	Angular acceleration feedback	6.674484 ± 0.0000078	34.16	0.0400
[26]	Torsion pendulum, time of swing	6.67349 ± 0.000026	1.56	0.0630
[26]	Torsion pendulum, time of swing	6.6726 ± 0.0005	20.98	0.0070
[27]	Torsion pendulum, time of swing	6.67433 ± 0.00013	117.42	0.1060
[28]	Laser interferometer	6.67234 ± 0.00014	480.00	1.5600
[29]	Torsion balance	6.67545 ± 0.00018	44.00	4.8000
[30]	Torsion balance	6.67559 ± 0.00027	48.00	4.8000
[31]	Torsion pendulum, time of swing	6.67349 ± 0.00018	1.58	0.0700

Panel B: Statistics for OLS Regressions Using Target Mass as the Independent Variable							
	Intercept			**Slope**			**Adj R^2**
	Value	**Standard Error**	***p*-Value**	**Value**	**Standard Error**	***p*-Value**	
OLS Regression	6.6743	0.00027	<0.0001	0.000204	0.000137	0.016	0.279
Bootstrapped standard errors (100,000 repetitions)	6.6744	0.00031	<0.0001	0.000202	0.000141	0.090	0.278

2.2. Planets' Orbital Dynamics

Consider the solar system with Sun of mass, $M_{\odot}$, and planets of mass, m_P, which are in a stable orbit at a distance of R_P, with a period T_P (so orbital velocity, V_P, equals

$2.\pi.R_P/T_P$). Assume that planets' orbits are stable, so that centripetal and centrifugal forces are equal. Under Newton's Law:

$$\frac{G \cdot M_{\odot} \cdot m_p}{R_P^2} = \frac{m_P \cdot V_P^2}{R_P} \tag{2}$$

$$\text{and}: \frac{R_P^3}{T_P^2} = \frac{G\,.\,M_{\odot}}{4 \cdot \pi^2} \tag{3}$$

This gives Kepler's Law where $\frac{R_P^3}{T_P^2}$ will be constant for planets, and—with $M_{\odot} = 2 \times 10^{30}$ kg—equal 3.36×10^{18}.

Panel A of Table 2 reports data from the International Astronomical Union [5] and NASA [32] that enable quantification of $\frac{R_P^3}{T_P^2}$ for planets. Neither source provides uncertainties for values, so error bars cannot be included. Equation (3) is plotted in Figure 2:

$$\frac{R_P^3}{T_P^2} \times 10^{-18} = 3.083 + 0.0051 \times \ln(m_p) = \frac{\hat{G} \cdot M_{\odot}}{4 \cdot \pi^2} \times 10^{-18} \tag{4}$$

$$\therefore \hat{G} = \left\{ 6.124 + 0.01004 \times \ln\left(m_{planet}\right) \right\} \times 10^{-11} \tag{5}$$

Table 2. Solar system data for natural experiments.

Panel A: Planet Characteristics								
	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Mass (kg $\times 10^{24}$)	0.33	4.87	5.97	0.64	1.898	568	86.8	102
Distance from Sun (m $\times 10^{10}$)	5.79	10.82	14.96	22.79	77.86	143.35	287.25	449.51
Orbital period (sec $\times 10^{7}$)	0.76	1.94	3.16	5.94	37.42	92.85	264.29	516.67
Panel B: Calculated Parameters								
Distance^3/Period^2 $\times 10^{16}$	335.8	336.1	336.3	336.0	337.1	341.7	339.3	340.2

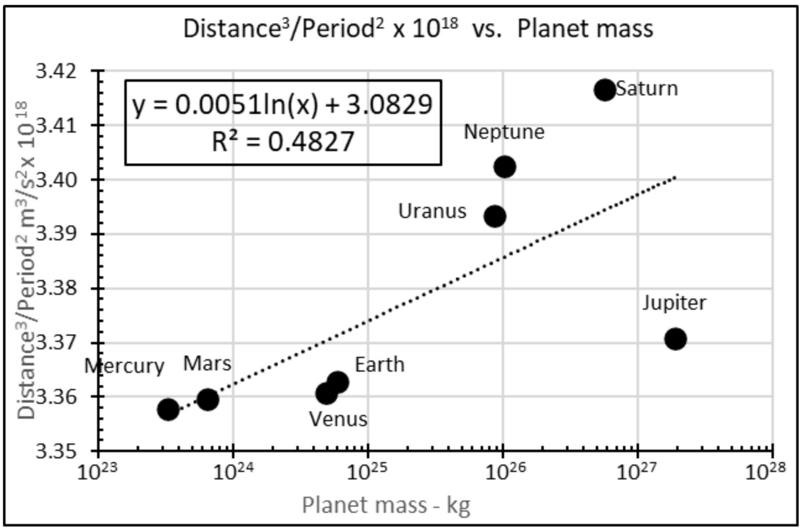

Figure 2. Planets' heliocentric distance and orbital period vs. mass (no uncertainties were provided for data).

2.3. Moons of Earth and Mars

The analysis above of planet orbital dynamics can be applied to planets' moons so that:

$$\hat{G} = \frac{R_{moon}^3}{T_{moon}^2} \frac{4 \cdot \pi^2}{M_{planet}} \quad (6)$$

Relevant data from NASA for the moons of Earth and Mars are shown in Table 3 [32].

Table 3. Data for planet moons.

	Moon	Phobos	Deimos
Mass (kg)	7.35×10^{22}	1.06×10^{16}	2.40×10^{15}
Distance from Planet (m)	3.84×10^{8}	9.38×10^{6}	2.35×10^{7}
Orbital period (sec)	2.36×10^{6}	2.76×10^{4}	1.09×0^{5}
Panel B: Calculated Parameters			
$\text{Distance}^3/\text{Period}^2 \times 10^{12}$	10.193	1.086	1.085

Starting with the Moon, data give a value of $\hat{G} = 6.739 \times 10^{-11}$.
For Martian moons, Figure 3 shows:

$$\frac{R_{moon}^3}{T_{moon}^2} \times 10^{-12} = 1.056 + 0.00082 \times \ln(m_p) = \frac{\hat{G} \cdot M_{Mars}}{4 \cdot \pi^2} \times 10^{-12} \quad (7)$$

$$\therefore \hat{G} = \{6.517 + 0.00516 \times \ln(m_{moon})\} \times 10^{-11} \quad (8)$$

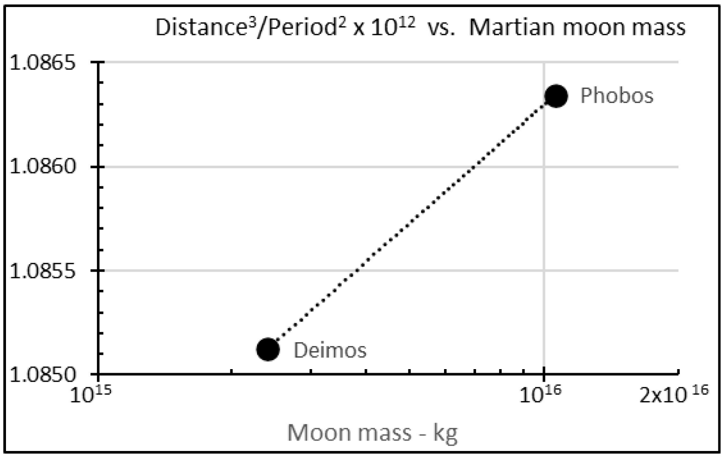

Figure 3. Martian moons' rotation curve and mass (no uncertainties were provided for data).

2.4. NGA of 'Oumuamua and Comets

As the first interstellar object identified in the solar system, 'Oumuamua, was the subject of intense scrutiny by a dozen astronomical teams over several months after late 2017 [33,34]. One of its most prominent features was NGA of 5.01×10^{-6} $m \cdot s^{-2}/R^2$, which reflects a reduction in solar gravitation of about 0.1 percent [8]. This is at the highest end of the range of NGAs observed in comets and asteroids [35] and triggered an extensive search for emissions that might explain it. However, none were observed, and 'Oumuamua was inert [36].

Positive NGA is away from the Sun, so that:

$$\text{NGA} = \text{Newtonian acceleration} - \text{observed solar acceleration} = \frac{M_{\odot}}{R_P^2} (G - \hat{G}) \quad (9)$$

$$\therefore \hat{G} = G - \frac{R_P^2}{M_\odot} \times NGA = 6.6743 \times 10^{-11} - \frac{(15 \times 10^{10}\ m)^2}{2 \times 10^{30}\ kg} \times 5.01 \times 10^{-6} = 6.6687 \times 10^{-11} \quad (10)$$

The last natural experiment relates to comets. The JPL Small Body Database maintained by NASA (available at https://ssd.jpl.nasa.gov/sbdb_query.cgi#x, accessed on 1 August 2021) [37] holds orbital dynamics and physical properties of more than 3700 comets and asteroids, with data on NGA and diameter available for 70 comets. This makes comets the numerically largest group with reported mass and orbital data, and thus their behavior informs the analysis of observed gravity.

Assuming density of comets' nucleus equal to 0.6 g/cm^3 [38], Figure 4 plots their NGA against estimated mass. Following the same approach as used with 'Oumuamua:

$$\begin{gathered} \hat{G} = 6.6743 \times 10^{-11} - 1.126 \times \{3.166 - 0.092680 \times \ln(m_{comet})\} \times 10^{-14} \\ \therefore \hat{G} = \{(6.6707 + 0.000104 \times \ln(m_{comet}) \times 10^{-11} \end{gathered} \quad (11)$$

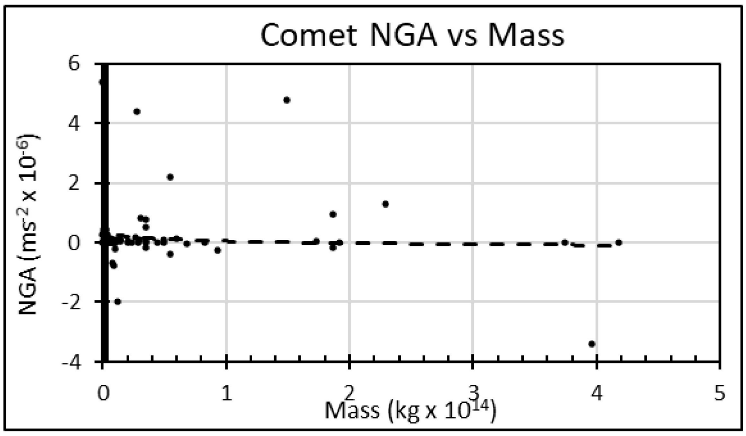

Figure 4. Comet NGA (in m/s^2) vs. estimated mass (kg) (1σ uncertainties are about ±10 percent).

Comet NGAs reported by JPL typically have 1σ uncertainty of ±10 percent, thus the relationship between $\hat{G}$ and comet mass is statistically insignificant. This, however, is counter-intuitive under the standard model of comet dynamics where NGA arises from the sublimation of volatiles on the sunward face of the comet, which induces positive (i.e., anti-Solar) NGA [39]. Because outgassing is a function of comet surface area and mass is a function of volume, NGA should be an inverse function of comet diameter and hence of the cube root of the mass. Thus the finding above is supportive of negative NGA related to comet mass and suggests that a portion of comets' observed NGA is a gravitational anomaly shared with other small bodies in the solar system.

2.5. Other Possible Gravity Anomalies

A number of other settings seemed suited to further natural experiments, but—in unreported results—none proved suitable.

One example is satellites' Earth flybys. However, data show inconsistent signs in anomalies, and recent values were zero, which suggests multiple effects that require more data to be untangled [40,41]. Moons of the outer planets were also checked for mass-related anomalies, as were flybys of Mars and its moons, but no significant anomaly was detected.

In addition, a number of gravity anomalies were explained, including the Pioneer anomaly and increase in orbital diameters of Earth and Moon [42].

3. Discussion

To summarise, the analysis above draws on six sets of data for planets and small bodies within the solar system, which avoids uncertain, confounding effects. Relying on Newton's Law of gravitation, data enabled quantification of observed gravitational constant, $\hat{G}$, and its values in different settings are summarised below:

Benchtop experiments $\hat{G} = \{6.674 + 0.000200 \times \ln(m_{target})\} \times 10^{-11}$

Planets' orbits $\hat{G} = \left\{6.124 + 0.01004 \times \ln\left(m_{planet}\right) \right\} \times 10^{-11}$

Martian moons $\hat{G} = \{6.517 + 0.00516 \times \ln(m_{moon}) \} \times 10^{-11}$

Earth's Moon $\hat{G} = 6.739 \times 10^{-11}$

'Oumuamua $\hat{G} = 6.6742 \times 10^{-11}$

Comets $\hat{G} = \{(6.6707 + 0.000104 \times \ln(m_{comet}) \} \times 10^{-11}$

Official (IAU) value of G $G = 6.6743 \times 10^{-11}\ m^3 \cdot kg^{-1} \cdot s^{-2}$ [5]

Figure 5 plots a representative value for each of the six lines of best fit above, which—when expressed in terms of G—can be expressed as:

$$\hat{G} = \{ G \times (0.998 + 0.000160 \times \ln(m)) \} \quad (12)$$

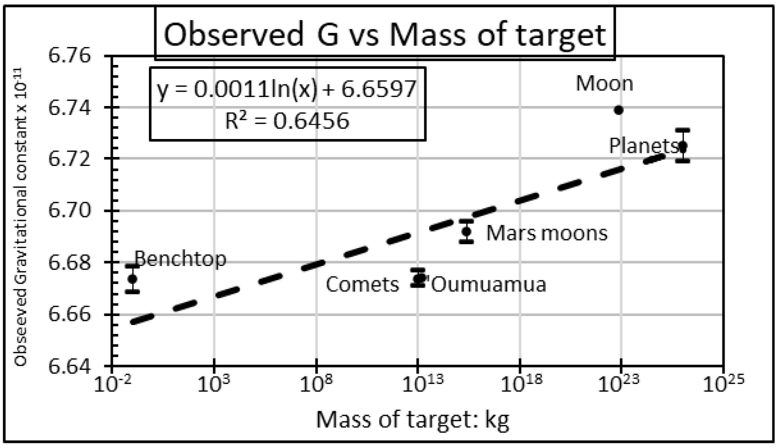

Figure 5. OLS regression parameters fitted to solar system bodies.

Equation (12) follows interpretation of data involving possible gravitational mass discrepancies in the solar system, and is a working formula because these data were generated for other purposes. In terms of the structure of the equation, in each natural experiment a log formulation had the highest statistical significance. Moreover, the structure of Equation (12) introduces a dimensionless factor that matches evidence whereby force increases disproportionately with a mass of the smaller, target object for masses in the range 0.01 kg to $M_\odot$ and over separation distances ranging from a few cm to 30 AU.

The first implication of Equation (12) is that the official value of G is accurate for $m \approx 10^6$ kg (typical of a 20 m diameter asteroid). For solar system bodies above that size, such as Earth, Equation (12) increases gravity by up to about 0.5 percent. For smaller bodies, it will reduce gravity and result in positive (i.e., anti-Solar) NGA. This scale-dependence has numerous corollaries. For example, when Equation (12) is applied to 'Oumuamua, which had radially outward NGA of about one-thousandth of solar gravitation, it suggests a mass of less than about 10^3 kg. While this is many orders of magnitude less than expected by most studies, it approximates the mass of typical manmade spacecraft and would be consistent with a light sail as proposed in reference [43].

Equation (12) also implies that gravitational anomalies within the solar system are consistent with scale-related Newtonian gravity. Newton's Law of Gravitation had been considered reliable in the solar system, so that—when unexplained gravity was identified at galactic scale and above—it was attributed to a phenomenon unique to those regions, either dark matter or dark energy [10]. The analysis here, though, shows that gravity is also scale-dependent within the solar system, which makes it universal and helps explain missing mass. Another possible implication of Equation (12) for the study of galaxies and beyond is the greater relative attraction of larger target masses which could explain the clumping of matter that leads to the formation of bigger than expected structures in shorter periods [44]. By relating G to m, Equation (12) also has implications for Newton's Law of gravitation which, for instance, could be revised to $F = \frac{G \cdot M \cdot m \cdot (0.998 + 0.00016 \times \ln(m))}{R^2}$, and for Kepler's and other Newtonian Laws, conservation of energy and momentum. More broadly, variation in determinations of G complements a variety of studies suggesting that it is not constant in all settings, but may vary over time [45], with location and alignment of apparatus [15] and time of day [46].

Without further work, such issues are difficult to evaluate. This points to the analysis' principal weak point, which is that reliance on published data to establish the nexus between gravitational mass and target mass gives an uncertain link and cannot rule out possible random and systematic errors. Thus, even though Equation (12) reduces cross-sectional variation in values of G in a variety of different settings by up to two-thirds, its limitations mean it is but one conclusion from the data. Further targeted studies are required to validate the findings. In the meantime, although initial findings foreshadow several possible implications, it is important not to over-reach the analysis.

Equation (12) explains part of the breakdown of Newton's Law but does not describe underlying physical processes, whether dipolar or other, and is probably only an approximation of a more comprehensive theory that requires further data and analysis. Even so, improved understanding of the well-studied behaviour of natural and artificial bodies in the solar system can only help tighten up natural laws.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used to support the findings of this study are included in the article. Table 1 lists sources of experimental determinations of G, the data on planets and moons are from NASA[32], and comet data are from the JPL Small Body Database available at https://ssd.jpl.nasa.gov/sbdb_query.cgi#x (accessed on 1 August 2021).

Acknowledgments: The author thanks the academic editor and three anonymous reviewers for insightful reports that significantly improved the manuscript.

Conflicts of Interest: The author declares that he has no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. There are no co-authors to the article, and I confirm sole authorship. There is no figure or text in the article that has been taken without attribution.

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