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The Gravitational Constant *G* May Decrease between Millimetre-Sized Masses

Qinghua Cui

Wuhan Institute of Physical Education, Wuhan, China
Email: cuiqinghua@bjmu.edu.cn

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Abstract

The Newtonian gravitational constant *G* is one of the most important fundamental constants of nature, but still remains resistant to the standard model of physics and disconnected from quantum theory. During the past >100 years, hundreds of *G* values have been measured to be ranging around 6.66 to 6.7559×10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ using macroscopic masses. More recently, however, a *G* value ($(6.04 \pm 0.06) \times 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$) measured using millimetre-sized masses shows significant deviation (by ~9%) from the reference *G* value, which the authors explained is resulted from "the known systematic uncertainties". However, based on the observation of historical *G* values and the protocol of the millimetre-sized masses based experiment, here we proposed a theory that this deviation is not from "systematic uncertainties" but actually *G* will rapidly decrease when masses sphere diameter is less than 0.02 metres. Moreover, this theory predicted the *G* value will be 5.96×10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ between masses whose diameter are 2 millimetres (0.002 metres), which matches the measured *G* value very well.

Keywords

Gravity, Gravitational Constant, Cosmic Microwave Background, Diffraction

1. Introduction

The Newtonian gravitational constant, *G*, is one of the most important fundamental constants of nature, however, it still represents one of the mysterious constants in Universe as the gravitational force remains resistant to the standard model of physics and disconnected from quantum theory [1]. Given its critical roles in many fields including theoretical physics, geophysics, astrophysics and astronomy, although the gravitational constant is most difficult to measure accurately [2], more than 200 experiments have been performed to identify the precise value of G since *Henry Cavendish* performed the first one more than 100 years ago [3]. As a result, the measured values of G are relatively stable from 6.66 to 6.7559 × 10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ [3]. Meanwhile, some modified gravity theories have been proposed [4]-[8]. Although non-Newtonian components in short range were suggested by some studies [9] [10], but there is still no clear evidence to support this opinion. More recently, a measurement between millimetre-sized masses (two gold spheres of 1 millimetre radius) was performed and determined a G value of (6.04 ± 0.06) × 10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ (Westphal *et al.* Nature 2021) [11], which deviates from the recommended CODATA value (G_{CODATA} = 6.67430 (15) × 10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$) by ~9%. This deviation is quite significant when compared with the measured values (**Figure 1**), even the values measured 100 years ago (6.67 × 10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ in 1873, deviates by only ~0.06%; 6.66 × 10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$ in 1895-1897, deviates by only ~0.2%). It is well known that these historical experiments have been performed using macroscopic masses at the kilogram scale and beyond. For this tension, the authors then explained "*This offset is fully covered by the known systematic uncertainties in our experiments, which include unwanted electrostatic, magnetic and gravitational influences from the masses and supports, as well as geometric uncertainties in the centre-of-mass distance due to the actual shape of the masses*". However, after carefully checking Westphal *et al.*'s experimental protocol and comprehensively surveying the historical G values, we found that Westphal *et al.*'s experiment was designed very well and it seems impossible that such a big deviation is resulted from "the known systematic uncertainties", as Westphal *et al.* considered. We previously proposed an equation that can precisely define G with cosmic microwave background (CMB) [12]. Based on this observation, here we propose a hypothesis that G may significantly decrease between very small-sized masses as single-slit diffraction may occur for CMB travel across these masses. As a result, the proposed theory explains the tension well.

2. Theoretical Equations and Analysis

To address the above tension, here we proposed the possibility that the value of G measured by Westphal *et al.* could be the true value at that scale of 1 millimetre radius mass. If this hypothesis is true, obviously new theory is needed.

We previously revealed a quantitative relation between the Newtonian gravitational constant G and the temperature T of the cosmic microwave background (CMB), by which G can be precisely determined by the temperature T of CMB as the following equation [12] [13].

$$G_T = \frac{T^2}{T_0^2} G_0 \tag{1}$$

where G_0 is the gravitational constant at present space-time with the CMB temperature of T_0, whereas G_T is the gravitational constant at the space-time with a CMB temperature of T. It is well known that CMB belongs to blackbody radiation. Thus, according to the following *Planck distribution function*,

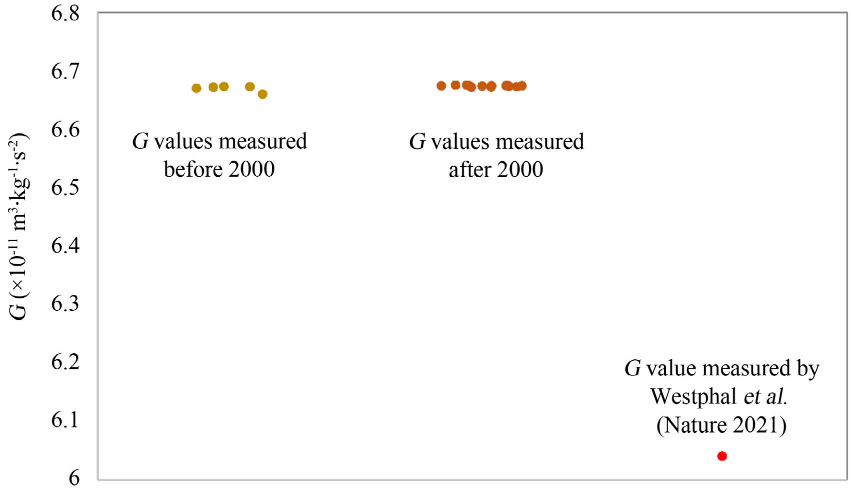

Figure 1. The distribution of the values of the gravitational constant G measured before 2000 and after 2000 according to the curation by Xue *et al.* [3], and the G value measured by Westphal *et al.* between millimetre-sized masses. This figure clearly shows that the G value between millimetre-sized masses significantly deviate from the ones measured using macroscopic masses.

$$u(\lambda)=\frac{8\pi h}{\lambda^3}\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1} \tag{2}$$

where h, c, k are *Planck*'s constant, speed of light in vacuum, and *Boltzmann*'s constant, and $u(\lambda)$ is the energy density of CMB radiation in the wavelength of λ, thus, the curve of the energy density of CMB radiation of the present space-time can be shown as **Figure 2(a)**. In **Figure 2(a)**, the x axis is the wavelength of various CMB electromagnetic wave components and the y axis is the corresponding energy density of specific electromagnetic wave component. The result showed that the peak energy density is located in ~0.005 metres (~5 millimetres) and the curve decreases sharply for CMB electromagnetic wave components with bigger or smaller wavelength (**Figure 2(a)**).

It is well known that during passing an obstacle having similar size with the wavelength, diffraction would be occur for the electromagnetic wave. Based on this observation, we thus proposed the following hypothesis. For two small-size masses (e.g. ≤5 millimetre diameter spheres), the CMB electromagnetic wave components whose wavelength equal to or less than the mass size would totally contribute to gravity, while the ones whose wavelength larger than the mass size would contribute to gravity only using its central energy in the diffraction pattern. Moreover, it is known that the light intensity of single-slit diffraction pattern obeys the following equation (details can be found at https://openstax.org/books/university-physics-volume-3/pages/4-2-intensity-in-single-slit-diffraction),

$$I=I_0\left(\frac{\sin(\beta)}{\beta}\right)^2 \tag{3}$$

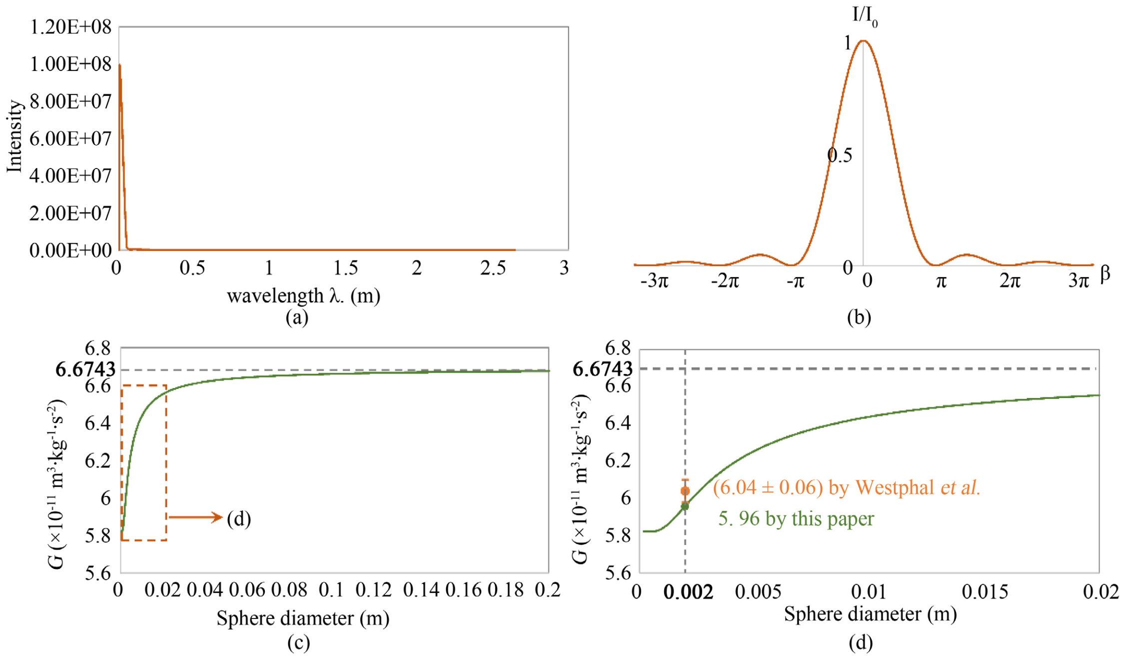

Figure 2. The distribution of energy density along wavelength for cosmic microwave background (CMB) radiation at the present space-time (a) and the distribution of light density for one specific electromagnetic wave during diffraction (b). The theoretical relation (green solid line) between the gravitational constant G and the mass sphere diameter ranging from 0.0002 to 0.2 meter (c). The horizontal dotted line indicates the reference G value. (c) clearly shows that the theoretically calculated G value decreases rapidly when mass sphere diameter becomes less than 0.02 meters. Moreover, a detailed theoretical relation (green solid line) between the gravitational constant G and the sphere diameter ranging from 0.0002 to 0.2 meters was shown as (d). The exact measured G value and the G value predicted by this theory for mass sphere with diameter of 0.002 meters are also given.

where β is the angle of diffraction and I_0 is the central maximal density. Figure 2(b) shows the density distribution for β ranging from −10 to 10. According to Equation (3) and Figure 2(b), it is clear that the density decreases rapidly to almost zero after −3π and 3π. It is thus not difficult to calculate the central energy would be ~93.4% of the total energy for one specific electromagnetic wave. Thus, the CMB energy E_d contributed to the gravity of the masses with size of diameter d can be described as

$$E_d = \sum_{\lambda<d} \frac{8\pi h}{\lambda^3} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1} + 0.934 \sum_{\lambda\geq d} \frac{8\pi h}{\lambda^3} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1} \tag{4}$$

Moreover, according to *Boltzmann*'s equation and Equation (1), the gravitational constant G_d for the masses with size of diameter d can be given as

$$G_d = \left(\frac{E_d}{E_{total}}\right)^2 G_0 \tag{5}$$

where E_{total} is the total energy of all of the CMB electromagnetic wave components.

3. Results

To confirm the above theory, we then calculated the relation of the gravitational constant G_d with the corresponding mass sphere diameter d ranging from 0.0002 to 0.2 metres using a widely accepted value of G (6.6743×10^{-11} $m^3 \cdot kg^{-1} \cdot s^{-2}$) as the reference G_0 value. As shown in **Figure 2(c)**, the value of G_d is quite stable and close to the reference G_0 value when the sphere diameter is greater than 0.02 meters, however, for mass spheres whose diameter less than 0.02 metres, G_d decreases rapidly (**Figure 2(c)** & **Figure 2(d)**). As a result, we calculated the theoretical value of G between 2 millimetre (0.002 metre) diameter spheres is $G_{theo} = 5.96 \times 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$, which matches the 13.5-h-long fitted value $G_{fit} = (5.89 \pm 0.20) \times 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$ and the long-term combined value $G_{comb} = (6.04 \pm 0.06) \times 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$ measured by Westphal *et al.* [11] very well (**Figure 2(d)**). Meanwhile, we provided the predicted G values between millimetre-sized masses from 1 mm diameter to 10 mm diameter in Table 1 and more details in Supplementary **Table 1** (available at http://www.cuilab.cn/bigg) which may be used to confirm the proposed theory or hypothesis in the future.

Table 1. List of ten predicted G values between 0.001 to 0.010 metre diameter masses.

Diameter (m)	Predicted G
0.001	5.839037878
0.002	5.960156502
0.003	6.086288679
0.004	6.18286802
0.005	6.255072918
0.006	6.310119073
0.007	6.353155485
0.008	6.387600802
0.009	6.415737827
0.010	6.439126274

Moreover, according to the current Hubble's constant (~70 km/s/Mpc), it is not difficult for this theory to predict that the G value is changing at a rate of −9.551246 × 10^{-21} $m^3 \cdot kg^{-1} \cdot s^{-2}$ per year, that is, $\dot{G}/G = -1.431048 \times 10^{-10}$ yr^{-1}, which is quite close to that derived according to changes in the earth's spin ($\dot{G}/G \propto -1.0 \times 10^{-10}$ yr^{-1}) [14], and that derived by lunar tidal acceleration, $\dot{G}/G = (-6.4 \pm 2.2) \times 10^{-11}$ yr^{-1} [15]. These results further supports the proposed theory from an alternative view of point.

4. Summary and Main Conclusion

In summary, we proposed a theory which can perfectly explain the tension between the newly measured G value of millimetre-sized masses and the established values. However, more experiments are needed to support this theory. For example, according to this theory, the gravitational constant between two aluminium spheres of the same mass with the gold spheres used in Westphal *et al.*'s study (diameter will be ~0.00385 metres) is predicted to be $G_{theo} = 6.17 \times 10^{-11}\ \text{m}^3\cdot\text{kg}^{-1}\cdot\text{s}^{-2}$. Similar experiments are needed to support this theory using multiple millimetre-sized and even submillimetre-sized masses. In addition, we only theoretically simulated diameter ranging from 0.0002 to 0.2 metres due to computing resource, theoretical simulation for the sub-atom scale (e.g. between electrons) is also necessary in the future. It should be noted that Fitzgerald *et al.* introduced 0.2 m as the length of small mass according to the maximum calculated gravitationally induced torque and torque due to Knudsen forces in their method for measuring G [16].

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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