The gravitational constant *G* may decrease between millimetre-sized masses

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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 values of *G* have been measured to be ranging from 6.66 to 6.7559×10^{-11} $m^3kg^{-1}s^{-2}$ using macroscopic masses. More recently, however, a *G* value ($(6.04\pm0.06)\times10^{-11}$ $m^3kg^{-1}s^{-2}$) 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, 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 meters. More important, the proposed theory matches the measured data very well, suggesting that *G* may indeed decrease rapidly when mass diameter smaller than millimetres.

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, the current best theory explaining all the other known forces well[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} $m^3kg^{-1}s^{-2}$ [3]. However, these experiments have mainly been performed using macroscopic masses at the kilogram scale and beyond. More recently, a measurement between millimeter-sized masses (two gold spheres of 1 millimetre radius) was performed and determined a *G* value of $(6.04\pm0.06)\times10^{-11}$ $m^3kg^{-1}s^{-2}$ (*Westphal* et al. *Nature* 2021)[4], which deviates from the recommended CODATA value (G_{CODATA}=$6.67430(15)\times10^{-11}$ $m^3kg^{-1}s^{-2}$) 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} $m^3kg^{-1}s^{-2}$ in 1873, deviation by only ~0.06%; 6.66×10^{-11} $m^3kg^{-1}s^{-2}$ in 1895-1897, deviation by only ~0.2%). 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". After carefully checking *Westphal* et al.'s experimental protocol, 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.

Theory

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 well determined by the temperature *T* of CMB as the following equation[5, 6].

$$G_T = \frac{T^2}{T_0^2} G_0 \qquad (1)$$

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 *Planck distribution function* (Eq.2),

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

where *h*, *c*, *k* are *Planck*'s constant, speed of light in vacuum, and *Boltzmann*'s constant, and *u(λ)* 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 2a. The *x* axis is the wavelength of various CMB electromagnetic wave components and the *y* axis is the energy density of corresponding electromagnetic wave components. The result showed that the peak energy density is located in ~0.005 meters and the curve decreases sharply for both CMB electromagnetic wave components with longer or shorter wavelength (Figure 2a). 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 its central energy in the diffraction pattern. It is well known that the light intensity of diffraction pattern obeys the following equation,

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

Where *β* is the angle of diffraction and I_0 is the central maximal density. Figure 2b shows that density distribution of *β* ranging from -10 to 10. According to Equation (3) and Figure 2b, it is clear that the density rapidly decreases to almost zero at –3π and 3π. It is thus not difficult to calculate the central energy would be ~93.4% of the total energy of the 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

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

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

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

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

Results

Based on 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 meters to 0.2 meters using a widely accepted value of G (6.6743×10^{-11} $m^3kg^{-1}s^{-2}$). As shown in Figure 2c, the value of G_d is quite stable and close to the reference G value when sphere diameter is greater than 0.02 meters, however, for mass spheres whose diameter less than 0.02 meters, G_d decreases rapidly (Figure 2c&d). As a result, we calculated the theoretical value of G between 2 millimetre (0.002 meter) diameter spheres is $G_{theo}=5.96\times10^{-11}$ $m^3kg^{-1}s^{-2}$, which matches the 13.5-h-long fitted value $G_{fit}=(5.89\pm0.20)\times10^{-11}$ $m^3kg^{-1}s^{-2}$ and the long-term combined value $G_{comb}=(6.04\pm0.06)\times10^{-11}$ $m^3kg^{-1}s^{-2}$ measured by *Westphal* et al.[4] very well (Figure 2d).

Conclusion

In summary, we proposed a theory which can explain the tension between the newly measured G value of millimeter-sized masses and the well 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 meters) is predicted to be $G_{theo}=6.17\times10^{-11}$ $m^3kg^{-1}s^{-2}$. In addition, we only theoretically simulated diameter ranging from 0.0002 to 0.2 meters due to computing resource, theoretical simulation for the sub-atom scale (e.g. between electrons) is also necessary in the future.

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Figure Legends

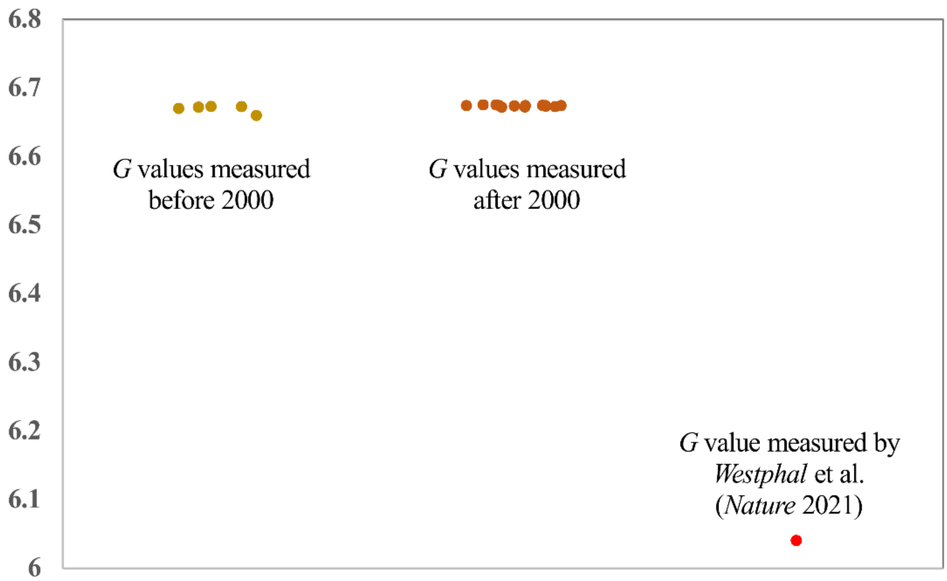

Figure 1. The distribution of the values the gravitational constant *G* measured before 2000 and after 2000 according to the curation by Xue et al. [3], and the *G* value measured by *Westphal* et al. between millimetre-sized masses. It is clear that the G value between millimetre-sized masses significantly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

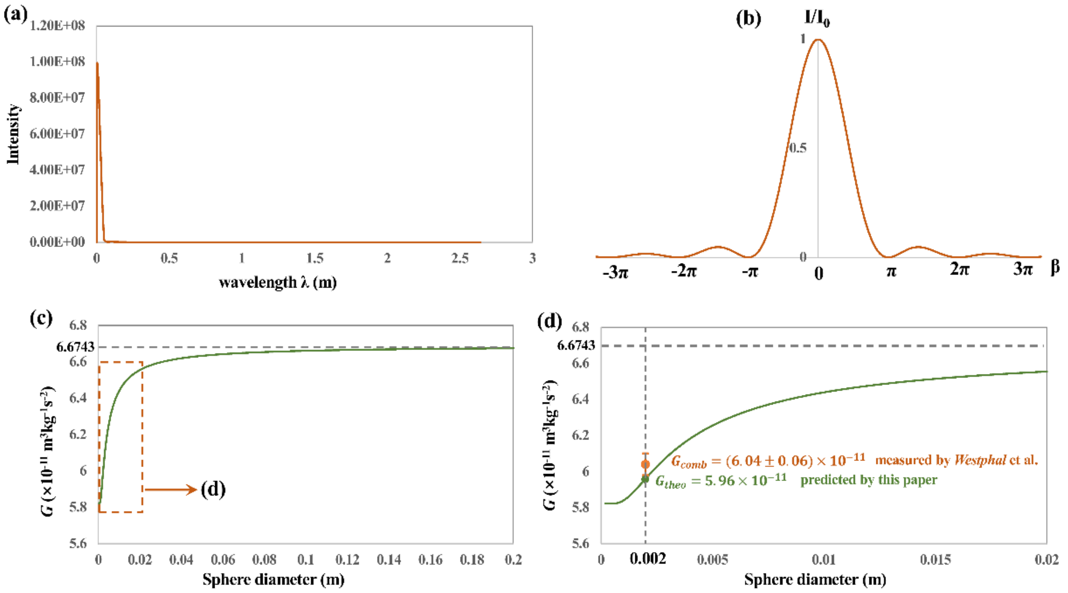

Figure 1. The distribution of energy density along wavelength for cosmic microwave background (CMB) radiation (a) and the distribution of light density for one specific electromagnetic wave during diffraction (b). The theoretical relation (green solid line) between the value of the gravitational constant *G* and the sphere diameter ranging from 0.0002 to 0.2 meters (c). The horizontal dotted line indicates the reference *G* value. It is quite clear that *G* decreases rapidly when mass sphere diameter becoming less than 0.02 meters. A detailed theoretical relation (green solid line) between the value of the gravitational constant *G* and the sphere diameter ranging from 0.0002 to 0.2 meters was shown as (d). The measured *G* value and the *G* value predicted by this theory for mass spheres at diameter of 0.002 are also given.