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Introduction

The Newtonian constant of gravitation—a constant too difficult to measure? An introduction

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It is generally accepted that the magnitude of the force attracting two spherical bodies of mass M_1 and M_2, separated by a distance r, is given by Newton's law of gravitation

$$F = G\frac{M_1 M_2}{r^2}.$$

The constant, G, determines the strength of Newton's inverse square law in a particular system of physical units and is, not surprisingly, known as Newton's constant of gravitation. It is considered to be a fundamental constant of nature. The current value for G in the 2010 CODATA recommended values of the fundamental physical constants is the best estimate given the experimental results available at that time [1] and is $G=6.67384(80)\times10^{-11}\,\text{kg}^{-1}\,\text{m}^3\,\text{s}^{-2}$. The current spread of values is approaching 0.05% (or 500 parts per million) which is more than 10 times the uncertainties on each measurement, and it therefore appears that we know G only to three significant figures! This is very poor compared with other physical constants, many of which have uncertainties of the order of parts in 10^8 and the constant determining the electronic structure of atoms, the Rydberg, has an uncertainty of only four parts in 10^{12}.

Why is G so badly known, why have recent experiments given such widely different results and how should we proceed now to resolve the problem? These were the questions addressed at the meeting held on 27 and 28 February 2014 of which papers in this issue of the *Philosophical Transactions A* are the proceedings.

Currently, gravity has a special place in physics as it is the only interaction that cannot be described by a quantum theory. Newton's law is seen to be an approximation to Einstein's general relativity, and both theories consider space and time to be continuous classical quantities, whereas the theories that describe electromagnetism and the nuclear forces are based on conserved quanta. Gravity is also by far the weakest force. A direct consequence of this is that the energy at which all the forces have comparable strength is close to the so-called Planck scale which is some 15 orders of magnitude higher than the energies currently being explored by the Large Hadron Collider. This fact calls into question the validity of the standard model of particle physics, as it is thought that this theory cannot be stable in the presence of such an immense fundamental energy scale. On the other hand, our confidence in Newtonian and Einsteinian gravity comes from carefully controlled experiments. The universality of free fall is an empirical foundation of Einstein's theory of gravity and states that the free acceleration of matter in a gravitational field does not depend on its chemical composition. Laboratory tests of the universality of free fall [2] and Newton's inverse square law on the scale of less than 1 m [3] use the same measuring devices and techniques as those used in determinations of G, as we describe further below. However, in order to perform the most sensitive tests and to relieve the burden of metrology, these experiments are cleverly designed to give a substantial signal only if nature misbehaves in the way sought out by the experimentalists. In determinations of G, we actually have to measure all relevant quantities in physical units and attack the metrology head on.

The actual numerical value of G has little importance in physics: the orbits of the planets in our Solar System are known to follow accurately Newton's law. For example, the orbital acceleration of a planet around the Sun is determined to a high accuracy by the product of the Sun's mass and G. Thus, finding a new value for G that is larger by, say, 0.05% from that given in the textbooks simply reduces our estimate of the Sun's mass by this amount. At present, we do not have models for the structure of the Sun that usefully constrain its mass at this level.

Adding to the mystique is the fact that gravity is the force that is most familiar to us as people living on the Earth. It is not surprising that reports in the media of significant discrepancies between experimental determinations of the value of Newton's constant of gravity can catch the public imagination, as the publication of our result did in October 2013 [4].

What matters then is not the actual value of G itself (give or take a percentage or so) but its *uncertainty*. The real importance of the accuracy of G is arguably that it can be taken as a measure, in popular culture, of how well we understand our most familiar force: the discrepant results may signify some new physics, or they may demonstrate that we do not understand the metrology of measuring weak forces. Owing to the lack of theoretical understanding of gravity, as alluded to earlier, there is an abundance of respectable theories that predict violations of the inverse square law or violations of the universality of free fall. In fact, a growing view is that G is not truly universal and may depend on matter density on astrophysical scales, for example. A misunderstanding of the metrology of weak force physics may in turn imply that the experimental tests that have established the inverse square law and the universality of free fall thus far are flawed in some subtle fashion. This makes for a potentially exciting situation and perhaps explains the general interest shown in our apparently mundane and painstaking work on G.

At the time of Newton and indeed up until the nineteenth century, the concept of a fundamental constant did not exist. Newton did not express his law of gravitation in a way that explicitly included a constant G, its presence was implied as if it had a value equal to 1. It was not until 1873 that Cornu and Bailey explicitly introduced a symbol for the coupling constant in Newton's law of gravity, in fact they called it f. It did not take its current designation G until sometime in the 1890s.

The development of the concept of fundamental constants was intimately linked to the development of systems of physical units. The international system of units (SI) will be based, from 2018, on fixed numerical values of seven fundamental constants, including the speed of light and Planck's constant, the latter being the constant appearing in the new definition of the kilogram [5]. Could we not define the kilogram in terms of G? For example, *the kilogram is the unit of mass, its magnitude is set by fixing the numerical value of G equal to* 6.67384…×10^{-11} $kg^{-1} m^3 s^{-2}$ *exactly.* In principle, we could do this, but the problem would be that any practical measurement of the mass of an object in terms of its gravitational attraction to another would have a precision of only a few parts in 10^4. This is about four orders of magnitude away from the precision we really need in our mass standards. Why is this? The principal answer is simply that gravity is too weak on the scale of laboratory-sized masses for it to be measurable with anything like the required precision. The gravitational force between a pair of 1 kg copper spheres just touching is about a thousand millionth of the weight of each, i.e. about 10^{-8} N. To measure this force, some way must be found to nullify the overwhelming downward force of gravity acting on both spheres.

A nearly perfect solution was found towards the end of the eighteenth century by the Rev. John Michell, who invented the torsion balance. By balancing two suspended balls hanging at the end of the torsion balance arm (which we now refer to as the test masses) from a long thin copper torsion wire, he realized that the downward force of gravity is neutralized, leaving the hanging balls sensitive to a sideways gravitational force produced by two much larger balls (the source masses) that can be moved to produce a positive and negative rotation of the balance. The torque constant, c, of the wire can be found by measuring the free period of oscillation ($2\pi/\omega$) of the torsion assembly and using the simple relation $c=I\omega^2$, where I is the moment of inertia about the vertical axis represented by the torsion wire. The apparatus was put to use by Henry Cavendish after Michell's death to measure G. His publication in 1798 describes in exquisite detail, arguably, the first precision experiment in physics and the 'Cavendish' torsion balance was one of the most significant pieces of physical apparatus ever invented. In a compilation of published work on measuring the gravitational constant, Gillies [6] listed about 350 papers almost all of which referred to work carried out with a torsion balance. Among the dozen or so experiments carried out over the past 30 years, all except two or three have been made with torsion balances. They have been protected not by wooden boxes as was the case for Cavendish but by vacuum chambers, but the basic principle of separating the minute gravitational force from the downward force of gravity has been that invented by Michell.

The papers in this issue demonstrate modern torsion balances and also novel methods of measuring G not based on the torsion balance. Common to them all is the requirement to make accurate measurements of mass, length and time (the unit of G being $kg^{-1} m^3 s^{-2}$) and often as well angle whose unit of course is of dimension 1. Key to all the work is the evaluation of the uncertainty and in most papers this occupies a significant place. Similarly, in the evaluation of the results leading to an

estimate of the best value, the comparative study of the uncertainties is the central task of the CODATA Task Group on Fundamental Constants.

The outcome of the discussion following the presentation of the papers at the Royal Society meeting was quite clear and is given at the end of this issue. It was clear that just one or two more determinations of *G* made by individual groups would not resolve the issue. Instead, a coordinated international effort was called for in which a small number of experiments would be carried out each of which would be followed in great detail by an international advisory board made up of those who already had experience of such work.

Footnotes

†Emeritus Director BIPM.

One contribution of 13 to a Theo Murphy Meeting Issue 'The Newtonian constant of gravitation, a constant too difficult to measure?'

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