FUNDAMENTAL CONSTANTS

Big *G* revisited

Measuring Newton's constant of gravitation is a difficult task, because gravity is the weakest of all the fundamental forces. An experiment involving two simple pendulums provides a seemingly accurate but surprising value.

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Newton's law of universal gravitation[1] is a pillar of classical physics. Here's a quick textbook example: the gravitational force between any two spherical objects is proportional to the product of their masses and inversely proportional to the square of the distance between their centres. If you know the value of each mass in kilograms and the distance between them in metres, the Newtonian constant of gravitation, *G* (aka big *G*), lets you calculate the gravitational force between the masses in units of ... newtons! Big *G* is one of the fundamental constants of physics[2]. Its value, which is roughly 6.674×10^{-11} $\mathrm{m^3\,kg^{-1}\,s^{-2}}$, can be established only by measurement. However, experiments with the potential to yield a highly accurate value of *G* are notoriously challenging. In a beautifully written article in *Physical Review Letters*[3], Parks and Faller describe an experiment carried out at the JILA institute in Boulder, Colorado, that has allowed them to measure *G* with an uncertainty of 0.0021%, or 21 parts per million (p.p.m.). This is among the smallest uncertainties ever achieved, but the derived value of *G* is a surprise.

The basic idea of Parks and Faller's experiment can be illustrated by a simple pendulum (Fig. 1a). When a 'source mass' is brought near the pendulum's bob (the 'test mass'), the gravitational attraction between the two masses causes the bob to move a small distance, *z*, from its usual rest position. Of course, the design and analysis of the real experiment are much more sophisticated than this simple depiction. The authors' experiment has two pairs of tungsten source masses and two identical pendulums, the copper bobs of which are pulled in opposite directions, and a host of other clever features.

The distance each bob moves is small: *z* is of the order of 50 nanometres. Yet the authors show that such small displacements can be

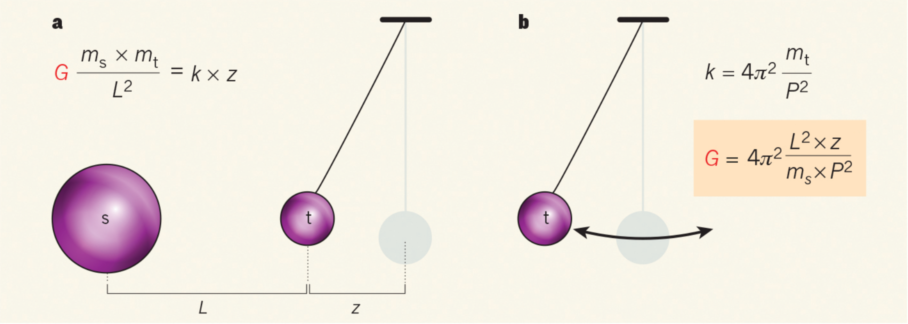

Figure 1 | The basic principle of Parks and Faller's experiment[3]. **a**, A spherical 'source mass' (m_s) is brought near a pendulum's spherical bob (the 'test mass', m_t) and causes the bob to move a small distance *z* from its usual resting position (grey). The gravitational force between the two masses (left side of equation), which depends on Newton's constant (*G*), can be obtained from a measurement of *z* provided that *k* is known (see **b**). **b**, The value of *k* is found by measuring the period (*P*) of the freely swinging pendulum. To compute the value of *G*, we need measurements of *L*, *z*, m_s and *P* (but not m_t). Parks and Faller's experiment was based on four cylindrical source masses of 100 kilograms each, two pendulums and many other refinements.

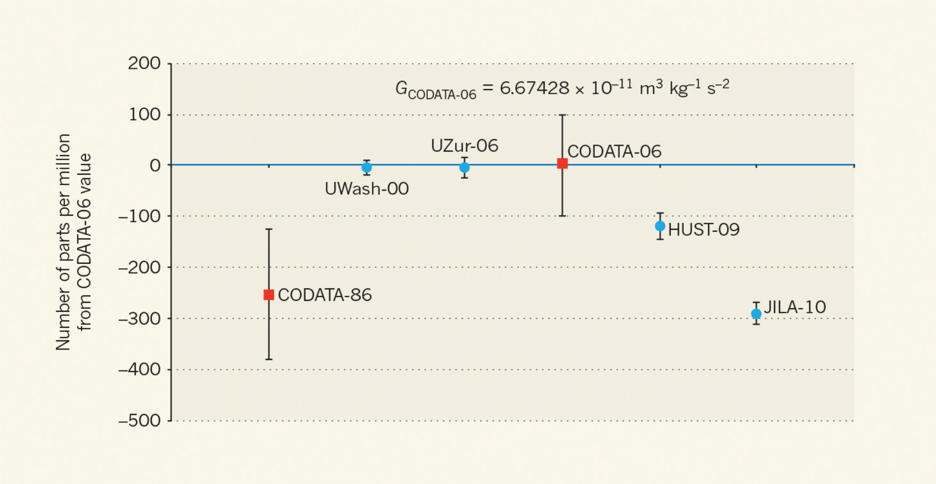

Figure 2 | Parks and Faller's estimate of big *G* in context. Parks and Faller find[3] a value for *G* (JILA-10) in agreement with the estimate of the CODATA-86 Task Group on Fundamental Constants but in disagreement with the CODATA-06 value[4]; from time to time, CODATA reviews and combines results from various experiments. Two of the measurements with the smallest uncertainty, UWash-00 (ref. 6) and UZur-06 (ref. 7), have been taken into account in determination of the CODATA-06 value. HUST-09 represents the culmination of an experiment that appeared in ref. 5 as HUST-99. All error bars denote 68% confidence levels.

measured with high accuracy. To measure the analogue of *z* in their experiment, Parks and Faller attached mirrors to the bobs and used modern optical techniques. Because precise optical measurements are impossible if the pendulums are swinging, the researchers installed powerful, permanent magnets beneath each bob so that a phenomenon called eddy-current damping would keep them still without affecting the values of *z*. But the magnets did create some small, subtle problems, which had to be identified and solved.

As a final step, the authors removed the magnets and source masses so that each pendulum could swing freely. This allowed the researchers to measure the period of each pendulum — the time it takes for the bob to complete one full swing — and, in turn, to derive the value of *G* from the measured distance (corresponding to *z* in Fig. 1b).

Here's the surprise: Parks and Faller's result[3] does not agree with the previous best estimate[4] of *G*, which was provided by the CODATA Task Group on Fundamental Constants (Fig. 2). CODATA regularly publishes an in-depth review of relevant experiments, followed by a list of recommended values and uncertainties for the fundamental constants of physics, including *G*. The last such publication, CODATA-06 (ref. 4), considered all results that were available until the start of 2007. (Earlier reports were dated 2002, 1998, 1986 and so on.)

To put the authors' work in context, it is helpful to know a bit of the recent history of big-*G* measurements. Typically, the set of credible *G* results available to CODATA is not consistent[5] for reasons that are seldom clear. Nevertheless, CODATA must produce its recommendation. In 1995, a new and highly discrepant experimental result led CODATA to increase the uncertainty assigned to *G* from 130 p.p.m. (1986) to a whopping 1,500 p.p.m. (1998), although it decided that the recommended value of *G* should not be changed. This unsatisfactory situation was a call to action, eventually leading to many new experimental results. By 2005, CODATA had sufficient reasons to exclude the discrepant 1995 value from further consideration[5].

The CODATA-06 recommended value for *G*, and the four experimental results that have the smallest estimated uncertainties ever reported, are shown in Figure 2. Interestingly, no two of these experiments use the same method to determine *G*. An uncertainty of only 14 p.p.m. is claimed by the University of Washington team[6] in Seattle (UWash-00), and this is still the record. This experiment[6] is elegant in both conception and execution. The University of Zurich group[7] (UZur-06) produced a remarkably similar result using a completely independent method. Problem solved? Not quite. The CODATA-06 error bars reflect the considerable scatter among the total set of *G* data that were considered[4] (only the two values with the smallest claimed uncertainties are shown in Fig. 2, and these results happen to agree perfectly). More recently, the group from the Huazhong University of Science and Technology in China (HUST-09) announced its final result[8]; and now, after extensive checking failed to uncover any errors in their work, Parks and Faller finally published[3] their *G* value (JILA-10).

Could something really fundamental be going on here? Probably not. It seems most unlikely that any discrepancies between different values could be due to a failure of classical physics to apply perfectly well to all of these experiments. Parks and Faller point out that their result agrees well with the CODATA-86 recommended value (Fig. 2). It is therefore interesting that CODATA has previously explained why it considers the key datum in the 1986 analysis to have been superseded by later work[5].

Ironically, because the authors' experiment has no evident flaw, their measurement may lead CODATA to increase the uncertainty of its next recommended value of *G*. Stay tuned. ■

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