Gravity on the balance

Despite intensified efforts, measurements of the gravitational constant continue to fail to converge, as **Terry Quinn** explains.

Since around 2000, eight new determinations of the gravitational constant *G* (also known as big G or Newton's constant) have appeared, almost all with declared uncertainties of about 20 ppm, but the total spread of the results is about 400 ppm. Two meetings in 2014 — one at the Royal Society in London, UK, in February 2014[1] and one later in the year at NIST (National Institute of Standards and Technology, USA) — resulted in a concrete proposal for coordinated action to try and resolve this problem[2]. But first, a little history.

Henry Cavendish was the first person to measure the gravitational attraction between two laboratory-sized masses. In his famous 1798 paper[3], he described an experiment to weigh the Earth using a torsion balance or, as we would now say, to determine *G*. (The introduction of the explicit coupling constant *G* appeared only at the end of the 19th century.) Cavendish was a superb experimenter: we estimate that he got it right to about 1%. Since then, most determinations of *G* have been made using a torsion balance, which provides almost perfect decoupling between the minute horizontal gravitational force acting on the two masses and their weight — a factor that easily exceeds 10^9.

The 1986 CODATA (Committee on Data for Science and Technology) evaluation of the fundamental constants[4] listed *G* with an uncertainty of 14 ppm, based on a 1982 value from the NBS (National Bureau of Standards, now NIST). However, in 1995 a new value from the PTB (Physikalisch-Technische Bundesanstalt, Germany) was published with an uncertainty below 100 ppm but with a value 0.64% above the CODATA one!

By the time the error in the PTB result had been uncovered, the flurry of activity on *G* had started[5]. A variety of methods were used, mostly torsion balances of different designs, including one at liquid-helium temperature. Others were based on suspended pendulums — a laboratory

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version of the method devised by Cavendish but carried out by Nevil Maskelyne in 1774, in which the deviation from the vertical of a hanging pendulum was measured close to a mountain — Schiehallion in Scotland (pictured). Yet another method used a balance to measure the difference in weight of a standard mass when thirteen tonnes of mercury was placed just above and just below it. A recent approach, involving the interferometry of atoms falling through a known gravitational field, has not yet reached their level of precision.

It was agreed at the 2014 NIST meeting that, as a first step, two of the recent measurements, those from JILA (Joint Institute for Laboratory Astrophysics, USA) and BIPM (Bureau International des Poids et Mesures, France) should be repeated in different laboratories. These are approximately 200 ppm below and 200 ppm above the mean, respectively. The equipment for both is still available and the BIPM apparatus will be transferred to NIST in early 2016. On a wider scale, an IUPAP (International Union of Pure and Applied Physics) workgroup on *G* was created and the CIPM (Comité International des Poids et Mesures) set up a consortium of national metrology institutes on the subject. Most recently, the US National Science Foundation published a call for proposals on *G*, mentioning funding between one and two million US dollars. In the announcement it was stated that "no experience is required"! Those cynics among us who have actually measured *G* would have added that the necessary experience will be acquired during the first ten years.

Who needs a more accurate numerical value of *G* (the current recommended value[6] is $6.67408 \pm 0.00031 \times 10^{-11}$ kg^{-1} m^3 s^{-2})? The short answer is, nobody, for the moment, but being apparently unable to converge on a value for *G* undermines our confidence in the metrology of small forces. Although it is true that the orbits of the planets depend on the product of *G* and the mass of the Sun — the structures of all astrophysical objects are determined by the balance of gravity and other forces produced by, for example, gas, photon or degeneracy pressure — *ab initio* models of the Sun are still an order of magnitude away from predicting a value of *G* at a level comparable with laboratory determinations. We do not need a value of *G* to test for departures from the inverse square law or the equivalence principle. There is as yet no prospect of a theory of quantum gravity that would predict a value for *G* that could be tested by experiment.

Could these unresolved discrepancies in *G* hide some new physics? This seems unlikely. I believe undiscovered systematic errors in all or some of these new experiments is the answer — *G* is difficult to measure but it should not be too difficult! ❐

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