The light stuff

Could we be surrounded by matter with negative mass? Physicist **Paul Wesson** is on its trail

THROW a ball in the air. Eventually, it will come back down to Earth. Unless, that is, your ball has a negative mass.

Negative mass? Who ever heard of an apple with a mass of minus 100 grams? Even antimatter has positive mass. In a recent series of experiments, most notably at the Stanford Linear Accelerator in California, researchers looked to see if positrons, the antimatter partners of electrons, fell upwards in the Earth's gravitational field. But like balls, people, and all the other matter that we know about, they fall towards the centre of the Earth.

Yet surprisingly enough, there is nothing in physics that rules out things having a negative mass. In fact, several leading physicists have dabbled with the idea over the years. Hermann Bondi at the University of Cambridge wondered why every positive mass could not be coupled with a negative mass, just as every magnet has both a north and a south pole. The late Fred Hoyle experimented with the idea that the mass of things increases as the universe ages, starting with zero at the big bang, which, conceivably, was preceded by a state where masses were negative. William Bonnor of Queen Mary, University of London, probed the laws of gravitational physics to see if they could include negative masses, and found they worked out fine.

So given that negative mass is not impossible, there is only one thing counting against it: we have seen no evidence. If it exists, where the heck is it?

One possible answer is that it is on the other side of the cosmos. Suppose the Earth had a negative mass. Then the Moon would be accelerated, driving it away from us. This leads to a strange picture: perhaps negative-mass objects are huddled together in the farthest reaches of the universe, like scared chickens in a cosmic coop.

It is possible, but not likely. Especially since we now have another, more plausible answer. My colleagues and I have found a tantalising clue about where to look for negative mass (*Journal of General Relativity and Gravitation*, vol 35, p 307).

The central issue behind this work is the weak equivalence principle. The WEP starts from the idea that matter could conceivably have two kinds of mass. One is the mass that produces, and feels, gravitational fields. This is called its gravitational mass. The bigger the gravitational mass of something, the stronger the pull it has on other things, and the more strongly it feels pulled by them. The other kind of mass is called inertial mass. This describes how hard it is to move an object out of its current state of motion or rest. Inertial mass determines the acceleration when an object is acted on by a force.

Thinking about mass in this way leads immediately to a question: is gravitational mass equivalent to inertial mass? The answer seems to be yes. It is the WEP that says a tennis ball will fall with the same acceleration as a cannonball (when air resistance is taken into account). The WEP also makes gravitational physics simple enough to be taught in schools. To illustrate this, consider what happens when we work out the orbit around the Earth (mass M) of the moon or some other smaller object (mass m). Newton's law tells us that the gravitational force varies as the inverse square of the distance r, and that a stable path involves an orbital velocity v. The orbit is obtained through the process of balancing the gravitational and centrifugal forces: $GMm/r^2 = mv^2/r$. On the left-hand side, the m is a gravitational mass; on the right, m is inertial. We say the ms cancel out; if it were not for the WEP, there would be no cancellation, and working out orbits would be a real headache. Indeed, most problems in gravitational physics can only be solved because of the WEP. (The Strong Principle goes further. It says, for example, that the constants of physics like the gravitational constant G, which mediate the forces, are the same everywhere in the universe. But that is a different story.)

The WEP has a deep significance: Einstein used it to formulate his general theory of relativity. Imagine yourself in a plummeting elevator: the WEP means there is no way to know whether you are falling in a gravitational field or simply moving at a constant velocity with no force (including gravitation) acting on you. Thus they must be the same thing: free fall is like having no force acting on you. As Newton made clear, that must mean that free-falling under the influence of gravity ▶

is the same as travelling in a "straight line" through space – and, in relativity, time. In Einstein's scheme, the motion of free bodies defines the lines of the geometric structure of space-time.

So far, all experiments, such as comparing the acceleration of different objects in free fall, back up Einstein's assumption that the WEP is correct (see "A brief history of equivalence"). The latest measurements show that gravitational mass and inertial mass can be considered equal with an accuracy of 1 part in 10^{12}. The status of the WEP appears secure – so secure that when Paul Dirac, the discoverer of antimatter, was informed of new plans to test its limits, he is reputed to have said: "You don't expect to find anything, do you?" However, it seems that the WEP is not quite as straightforward as we once thought.

Hidden complexity

There are several theories of physics in vogue that extend the four dimensions of space and time in ways that unify the known fundamental forces. The basic idea is that, while we see four dimensions, the real world has more. How many more is a moot point among physicists: an average edition of a theoretical physics journal will typically contain articles on 10D supersymmetry, 11D supergravity and even 26D string theory. A journal of this type, falling into the hands of a student, would be lucky to find use as a doorstop. However, such a student might find solace in a consensus opinion: the basic extension of general relativity into five dimensions is actually pretty useful, and provides the easiest way to test the plausibility of higher-dimensional theories.

Our perspective on this is that the WEP stems from a higher-dimensional theory of gravity. When my colleagues and I rewrote the equations of general relativity in five dimensions, something very interesting fell out. Our formulation seems to show that in five dimensions, the traditional form of the principle can break down.

When we solved the equations in five dimensions we found that there is an extra force, which depends on the motion of the normal 4D space-time with respect to the fifth dimension. The way a particle accelerates in this 5D scheme depends on the mass of the particle – a clear violation of the WEP. And nestling in the 5D solutions to some of Einstein's equations is something that may finally prove that the WEP can be violated: a hint of where to look for negative mass.

In our solutions, the mass that affects

A brief history of equivalence

EXPERIMENTER/PROJECT	YEAR	SENSITIVITY	METHOD
Philiponus	500 (?)	"small"	Drop tower
Galileo	1590 (?)	10^{-2}	Drop tower
Newton	1686	10^{-3}	Pendulum
Bessel	1832	10^{-5}	Pendulum
Potter	1923	10^{-6}	Pendulum
Eotvos	1922	10^{-8}	Torsion balance
Dicke	1964	10^{-11}	Torsion balance
Braginskii & Panov	1972	10^{-12}	Torsion balance
Shapiro	1976	10^{-12}	Lunar laser-ranging
Adelberger	1990	10^{-12}	Torsion balance
APOLLO	2006?	10^{-14}	Lunar laser-ranging
Microscope	2008?	10^{-15}	Earth orbit
STEP	2011?	10^{-18}	Earth orbit

SOURCE: STEP PROJECT

The equivalence principle is enormously important to modern physics. It can be reduced to a simple question: does gravity affect different materials in different ways? Although Aristotle thought so, the answer seems to be no: drop a cannonball and a tennis ball off a tower and they will accelerate at exactly the same rate – once any difference in air resistance is taken into consideration.

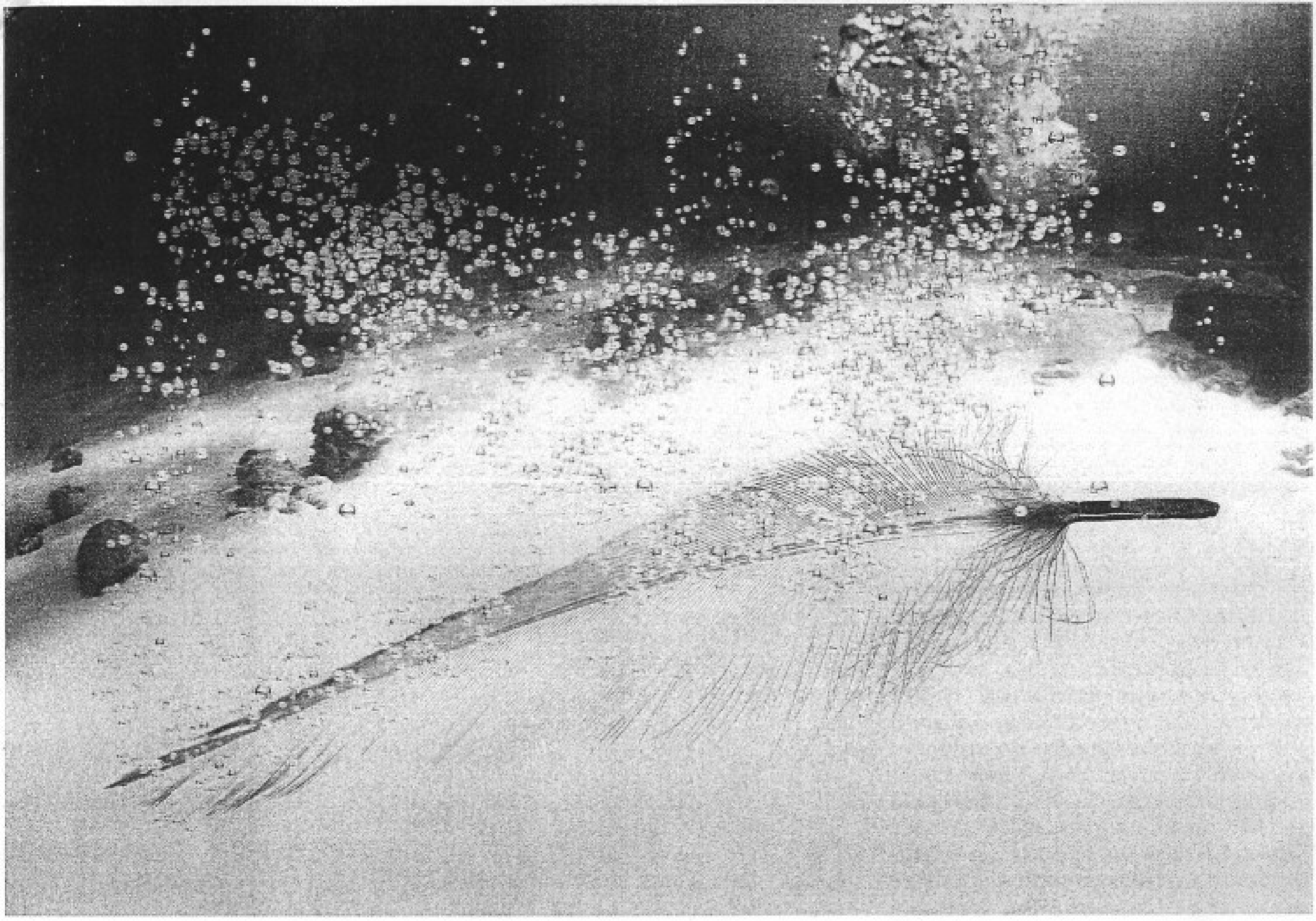
The first recorded experimental test of the principle was in the 5th century, by a Byzantine philosopher called Iohannes Philiponus. In a commentary on Aristotle's *Physics*, Philiponus described – and possibly performed (nobody knows) – a drop-test of different masses.

Galileo's experiment in 1620 of dropping a musket ball and a cannonball from the leaning Tower of Pisa in Italy is possibly a myth. But we know Newton was aware of experimental proofs of the equivalence principle by 1685. He was the first to appreciate how important this was: it meant that gravity was the only force whose action made no distinction between materials.

In the early 20th century Einstein made the principle the bedrock for his general theory of relativity. Relativity, of course, is well-tested. So how convinced are we by the equivalence principle? We know that the mass that reacts to gravity (gravitational mass) and the mass that reacts to an applied force (inertial mass) are equivalent to within one part in 10^{12}. There are hopes that experiments planned for the near future will improve on this accuracy.

The APOLLO project, based at Apache Point, New Mexico, will test the WEP to one part in 10^{14} within a couple of years. APOLLO will use "lunar laser-ranging" to do this, bouncing laser light off the moon to look for eccentricities in the way the moon and Earth behave in the sun's gravitational field.

In 2008, the European Space Agency (ESA) will launch a space-based test of equivalence called Microscope. This will watch how two platinum and titanium cylinders fall during a flight inside a satellite 1000 kilometres above Earth. Within a year of launch, the project's researchers should have a measure of equivalence to one part in 10^{15}. And some time after 2011, a joint ESA-NASA project called the Satellite Test of the Equivalence Principle is hoping to use a similar experiment to take the test of equivalence up to one part in 10^{18}. Michael Brooks



"The best candidate for exposing negative mass might be the centre of a neutron star"

the acceleration appears in two different ways. For solutions of the theory that correspond to physical systems we already know about – anything composed of ordinary matter – the negative or positive sign of the mass is masked by the fact that it appears in the equations as mass squared. Unfortunately, that means that we cannot show the existence of negative mass using common-or-garden astrophysical systems.

But we also have solutions that are sensitive to the sign of the mass. These correspond to exotic systems that exist in conditions of enormously intense gravitational fields, such as the event horizon of a black hole. Might we be able to see evidence of negative mass in such systems in the next decade? It is just about possible.

An experiment to test the equivalence of gravitational and inertial mass to one part in 10^{18} is scheduled for launch sometime after 2011. The proposed satellite test of the equivalence principle (STEP) will involve four metal cylinders (each made of a different metal and having a different mass) free-falling for around 16 minutes in orbit. With the unprecedented sensitivity of STEP's equipment and this extremely long "drop" time, there is an outside chance that one sample might fall measurably faster than another. This violation of the WEP (and thus relativity) would be a revolutionary observation, showing that negative mass arises from the poorly-understood forces operating deep within an atomic nucleus.

My colleagues and I will be spending the next two years calculating what might be the necessary conditions for STEP to see such an anomaly. It is a long shot, of course; the chances are that we won't see any such thing. But it is no more of a long shot than the long-running and considerably more expensive search for magnetic monopoles, another form of exotica suggested by the laws of physics. Whatever the outcome, we will have pinned down the possibilities a little more tightly.

If STEP fails to spot negative mass all is not lost, but finding it will then be even harder. It could show up in the exotic material that might – in the time-travel scheme dreamed up by Kip Thorne and Stephen Hawking – hold open the neck of the wormholes that provide a shortcut through space-time. The best candidate for exposing negative mass might turn out to be the centre of a collapsed star, where gravitational forces are extremely intense. Over the years, physicists have been slowly refining the equations of state of neutron stars, and it seems that somewhere in their centres we might indeed find traces of negative mass. Of course, exposing this will require large test masses, so we will need something big to fall into the collapsing star – something like the Earth, perhaps.

While free-falling towards the star, we might just be able to make that crucial measurement. Done this way, the existence of negative mass would be our last scientific discovery. But worth it, surely? ●

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