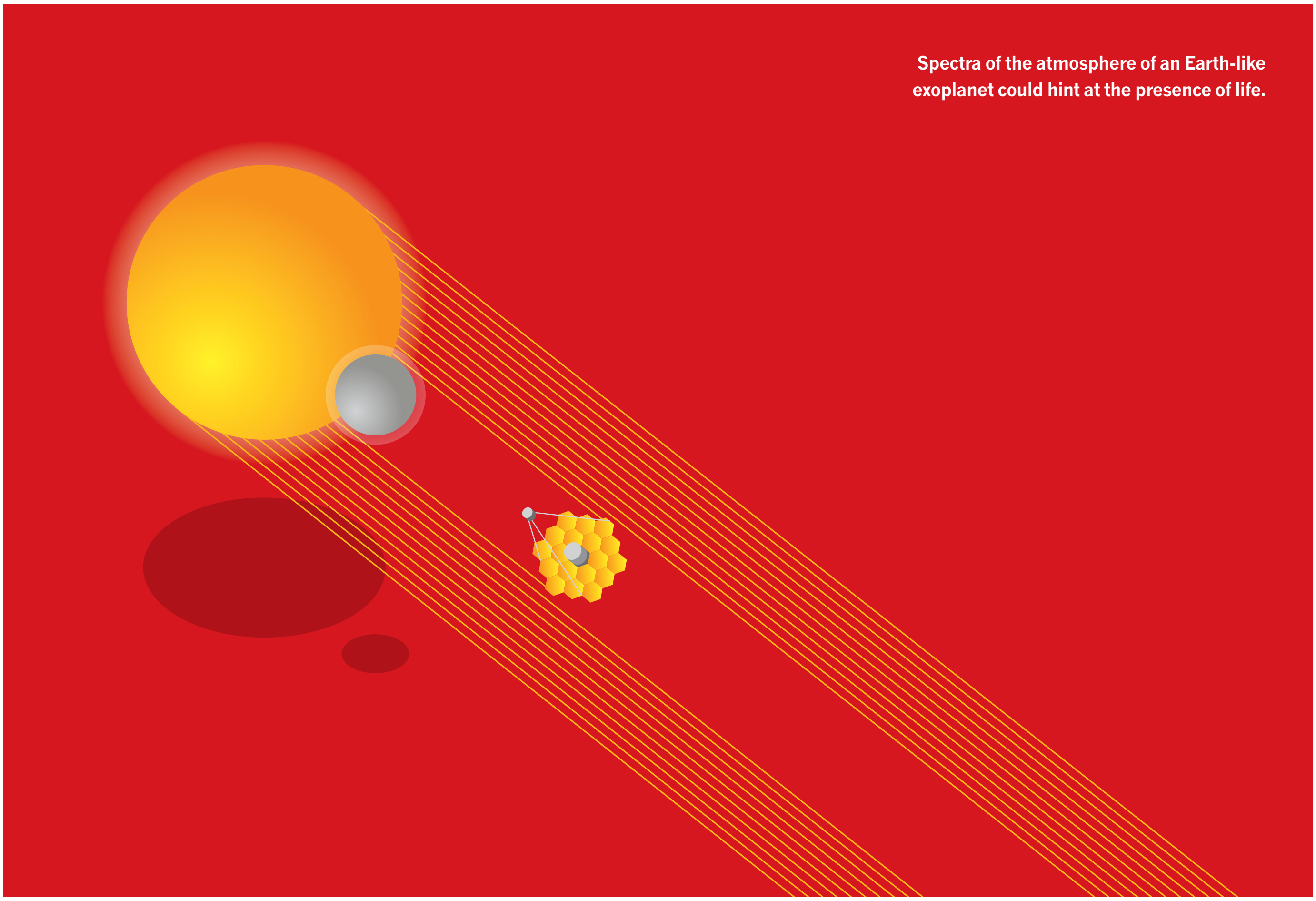


Spectra of the atmosphere of an Earth-like exoplanet could hint at the presence of life.

ILLUSTRATIONS BY THOMAS POROSTOCKY

TOUGH SCIENCE

Five experiments as hard as finding the Higgs.

BY NICOLA JONES

As the media spotlight shines on the Large Hadron Collider in Geneva and its high-profile hunt for a certain boson, other scientists are pressing forward with experiments that are just as challenging — and just as potentially transformative.

These often unsung researchers are willing to spend years or even decades getting a finicky instrument to run smoothly; setting up proper controls to minimize spurious results; beating back noise that threatens to swamp their signal; and striving for an ever more painstaking level of precision — a determination and single-mindedness that borders on heroic. Here, *Nature* describes five such quests.

SPOTTING DISTANT SIGNS OF LIFE

Back in 1999, when David Charbonneau was a graduate student at Harvard University in Cambridge, Massachusetts, he became the first person to measure the tiny dimming caused by the passage of a planet from another solar system across the face of its parent star. Today, such 'transits' are a routine way for astronomers to discover planets. The tricky part is working out what they and their atmospheres are made of. If the atmosphere turns out to contain oxygen, for instance, that could be an indication of the presence of life. But the only way to detect such elements is to find them in the spectrum of the starlight that passes through the planet's atmosphere — a signal that is ridiculously small.

To begin with, explains Charbonneau, "the fraction of light that the planet blocks is tiny". A planet the size of Jupiter passing in front of a star like the Sun would block about 1% of the light; and a smaller, Earth-size planet would block about 0.01%. "Then you look at this tiny onion skin around the planet: that's the atmosphere," Charbonneau says. Only the starlight that passes through that onion skin will have the spectral information that astronomers are looking for — and that's less than one photon in a million for a Sun-like star and a planet the size of Earth.

Although no telescope today has anywhere near the sensitivity required to extract a signal that small from the glare of the star itself, Jupiter-scale gas-giant planets have much bigger atmospheres than Earth-sized ones and a correspondingly bigger spectral signature, says Charbonneau. Orbital observatories such as the Hubble and Spitzer space telescopes have been able to extract atmospheric spectra for about 40 gas giants, all since 2005. Although the initial observations met with scepticism, says Charbonneau, "for the gas giants, it's now not quite commonplace, but not controversial. Now it's all about Earth-like planets, but no one has done that yet." The closest researchers have come is examining the spectra of a super-Earth — called GJ 1214b — that has a radius about 2.6 times that of Earth's and is circling a relatively small star not too far from the Sun. The first work on this planet implied that it had an atmosphere full of water vapour or clouds; observations by Charbonneau and his colleagues using Hubble confirmed this a few months ago[1].

Detecting the components of the atmosphere of an Earth-like planet around a Sun-like star — affording the best chance of detecting biological activity on another planet — requires a step-up in sensitivity. Charbonneau is crossing his fingers and hoping that NASA's long-planned and much-delayed Hubble successor, the US$8-billion James Webb Space Telescope, now scheduled for launch in 2018, will indeed reach orbit. "That would be fantastic," he says. "That would give us an honest shot at finding life on other planets."

SEEING THROUGH THE MOLECULAR MIRROR

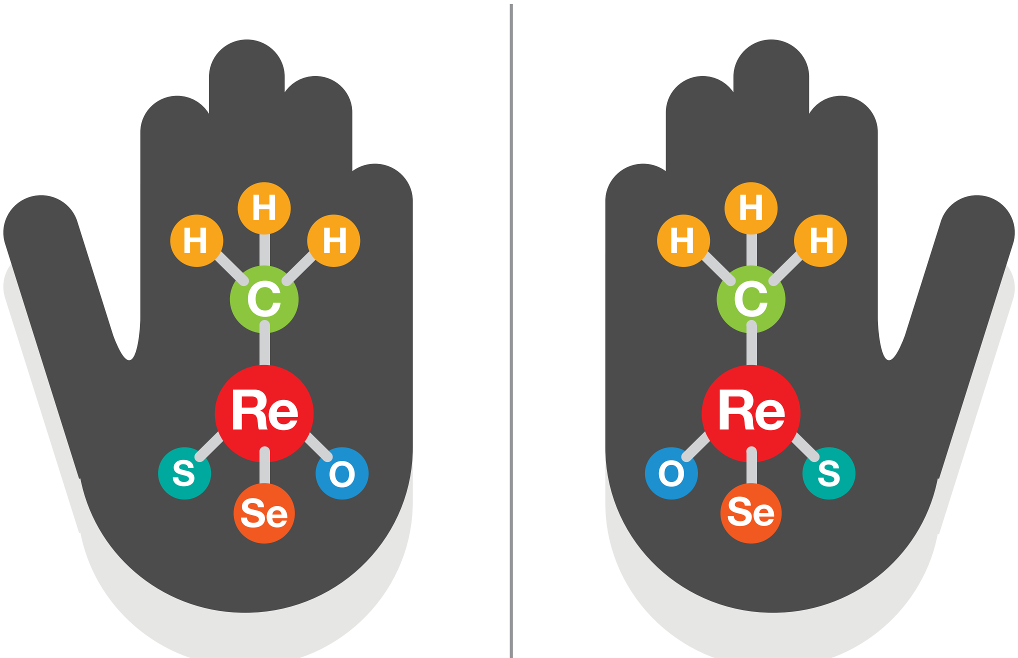
Biology has a curious lopsidedness. Many molecules are 'chiral', meaning that their atoms can be arranged in two forms that are mirror images of each other. When making such molecules in the lab, chemists typically get a mix of both forms, which, by convention, they label as right- or left-handed. But living cells are generally made from the left-handed versions only. No one knows why.

One possible explanation lies in the fact that one of the four fundamental forces in nature predicted by the standard model of particle physics — the 'weak' force that mediates certain interactions between nuclei and electrons — affects left- and right-handed molecules differently. The other forces, which include gravity, are the same in either version of a mirror universe. In theory, explains Benoît Darquié at the University of Paris 13 North in Villetaneuse, France, the weak force should cause the energy states in one form of a chiral molecule to be ever so slightly different from those in its mirror image twin — typically by just one part in 10^{15} or 10^{20}. So if one form had a vibrational frequency of, say, 30 terahertz, its partner's should differ by just a few milli- or even microhertz.

> "THE HARDER IT IS, ALL THE BETTER IT FEELS WHEN YOU GET THERE."

Measuring such tiny differences could shed light on the biological lopsidedness conundrum, says Darquié, and his group is attempting to do just that. It could even fill in the values of certain parameters in the weak-force theory part of the standard model.

He and his colleagues are the only ones in the world pursuing this goal, as far as Darquié knows. Indeed, it took him a full three years to assemble the consortium of experimental physicists, quantum theoreticians and chemists he needed. They now need to crack two problems. First, they need to build extremely high-resolution spectrometers to measure the energy levels of chiral molecules. Their best instrument to date can discern energy differences as small as 5 parts in 10^{14} — about a million times better than the resolution of an off-the-shelf spectrometer. They are now building one that will be even more precise. To achieve such sensitivity, their machines need to be isolated from any external vibrations and maintained at a temperature that is steady to within 0.1 °C. And to measure the molecular vibrational frequencies with the required level of precision, Darquié's lab uses a molecular



Tiny differences in the energy levels in mirror-image molecules could hint at symmetry-breaking weak interactions.

clock linked by a fibre-optic cable to the world time standard atomic clock in Paris.

The researchers' second challenge is to create test molecules in which the asymmetrical effect is large enough to be measurable. Such a molecule needs to have a large central atom, because atomic theory says that will maximize the energy differences between the chiral forms, and must not break apart when heated to the gaseous state necessary for spectroscopy. The team is betting that the best molecule will be something like methyltrioxorhenium that has had two of its oxygen atoms replaced by sulphur and selenium, although the researchers have struggled to make that particular molecule in purely left- or right-handed forms. Even if the researchers find a molecule that works perfectly, they will still need another year to take enough measurements to bump up the signal-to-noise ratio and get a trustworthy number.

What if the experiment doesn't solve the puzzle of biological handedness? Darquié says that it won't bother him much, because the techniques they are developing will open up a lot of ways to test the theories of fundamental physics. "Most of the accurate tests are done at high energy with particles, or at lower energies with atoms," he says. "Molecules are more complex, so give access to more complex questions."

LOOKING FOR EXTRA DIMENSIONS

It is an aspect of reality so fundamental that most us can't imagine anything different: the world has precisely three spatial dimensions — left–right, forwards–backwards and up–down. But superstring theory and other attempts to devise a 'theory of everything' have led many physicists to propose that space has many more than that. These extra dimensions would presumably be curled up very tightly, and thus hidden from everyday experience. But they would affect gravity at very small scales, producing a force between two masses that differs ever so slightly from that predicted by Newton's classical law of gravity. An experiment able to detect changes in gravity at that scale might therefore be able to 'see' any other dimensions.

Eric Adelberger at the University of Washington's Center for Experimental Nuclear Physics and Astrophysics in Seattle first heard about this idea at a talk back in 1999. "Some people thought it was crazy; some thought it was really cool," he says. But he and his colleagues decided they had to test it. "What more exciting thing can you do than discover that our understanding of the dimensionality of the world has been wrong forever?" he says.

The team's tool of choice is a torsion balance — essentially an update of the equipment used by the English physicist Henry Cavendish to make the first laboratory measurement of gravity in the late 1790s. In the modern version, a metal cylinder hangs from a thread, allowing the cylinder to twist freely. Attached to the bottom of the cylinder is a disk called the detector, which has a ring of holes drilled in it. A second disk, with similarly drilled holes, sits just micrometres beneath this. When this second disk, called the attractor, is rotated, the material between its holes exerts a tiny gravitational force on the material between the holes in the detector. The force twists the thread that supports the cylinder, causing it to rotate by an amount measured in billionths of a degree.

Micrometre-scale rotations could hint at deviations from Newton's law of gravity caused by extra dimensions.

To make sure that the detector is responding to gravity and nothing else, the equipment has to be made entirely from non-magnetic materials, and all the surfaces need to be coated in gold to spread out any electrical charges on the device. The device also has to be machined to perfection and protected from all vibrations, including cars driving into the car parks outside. "We get our best data on weekends from midnight to 4 a.m.," says Adelberger. "It's frustrating. The amount of time you spend actually getting good data is very small. It's all detective work."

Tweaks to the design allow the experimenters to cancel out the force expected from Newton's law and isolate the deviations: if the detector spins anyway, they know that something funny is going on. And so far, Adelberger's group can say definitively that there are no extra dimensions larger than 44 micrometres. Two of his graduate students, as well as a handful of other groups around the world, are trying to push that limit down, he says. But how long it will take them to spot something depends on the size of the elusive dimensions. If they're curled up too tightly, he says, "the answer is never. If there is one at 30 micrometres, it'll be a year".

But Adelberger seems to thrive on the uncertainties and difficulties involved. It's like getting to the top of a mountain, he says. "The harder it is, all the better it feels when you get there."

CATCHING A GRAVITY WAVE

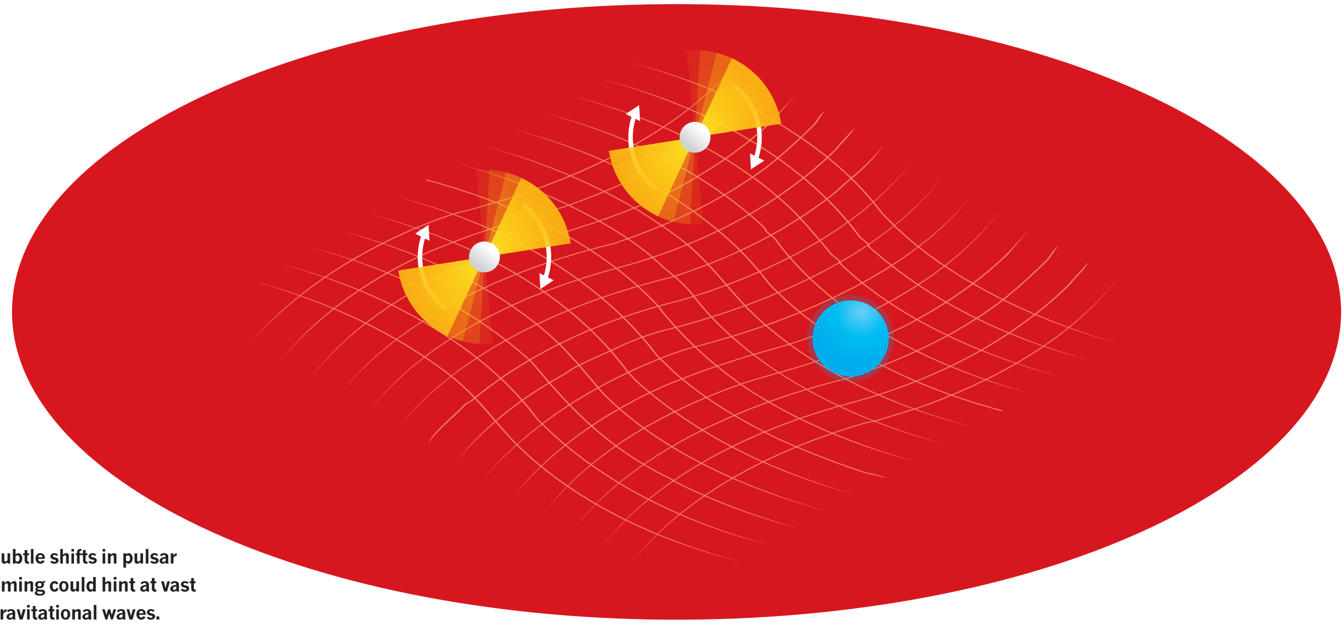
Scott Ransom has a boyish energy that seems mismatched with his subject: a project that may take a decade to produce its first result. Ransom, an astronomer at the National Radio Astronomy Observatory in Charlottesville, Virginia, uses a rapid-fire stream of words such as "awesome" and "cool" as he talks about the Galaxy's most precise natural clocks — pulsars — and how they might allow him and others to detect one of the most fundamental predictions of Einstein's general theory of relativity: gravitational waves. "It will open a whole new window on our Universe," he exclaims. "We will be able to see with mass instead of light."

According to Einstein, explains Ransom, gravity waves are ripples in the fabric of space-time caused by the movement of mass — an orbiting pair of neutron stars, for example. It's just like jiggling an electron, which causes ripples in the surrounding electric and magnetic fields to spread out as light and other forms of radiation. "When you jiggle something massive," he says, "you give off gravitational waves".

Unfortunately, even a very big gravitational wave washing over Earth would squash and expand the planet's diameter by only 10 nanometres or less. Ground-based experiments attempting to detect such tiny disturbances, such as the Laser Interferometer Gravitational wave Observatory run by the California Institute of Technology in Pasadena and the Massachusetts Institute of Technology in Cambridge, are forever trying to distinguish genuine signals from background noise caused by passing trucks, thunderstorms and even the fall of waves on a beach a hundred kilometres away.

So Ransom and his fellow enthusiasts are taking what they hope will be a cheaper path: looking at pulsars. Some of these ultra-dense stars rotate thousands of times a second, each time emitting a flash of radiation that astronomers can time to within about 100 nanoseconds. The team hopes to monitor about 20 such pulsars spread all over the sky to look for deviations in their timing caused by very-low-frequency gravity waves contracting or expanding the space-time between them and Earth. They expect that one of the strongest sources of such waves is the years-long dance of massive black holes in distant, colliding galaxies.

Ransom is one of about a dozen people devoted to this quest, which



Subtle shifts in pulsar timing could hint at vast gravitational waves.

is coordinated by the International Pulsar Timing Array consortium. The good news is they haven't needed to invent any instruments: facilities such as the Arecibo radio telescope in Puerto Rico can do the job. The bad news is that the pulsars need to be monitored for around 10 years to catch the gravitational waves from those orbiting black holes. So far, they have accurate timing measurements for about 5 years on just 6 pulsars.

Still, says an upbeat Ransom, "the cool thing is that our chance of discovery goes up dramatically with time. As long as we're patient, we will see gravitational waves."

REDEFINING THE KILOGRAM

The mass of one kilogram is meant to be an unvarying constant. Yet it actually changes, thanks to an old-fashioned way of defining it as the mass of a more-than-120-year-old cylinder of platinum and iridium that lives in a vault in the outskirts of Paris. No one knows if 'Le Grand K' is getting heavier as atoms are added to its surface, or lighter as atoms are rubbed away, but its mass is certainly drifting: copies that once had precisely the same weight now have measurably different weights.

"We need to tidy things up," says Jon Pratt, an engineer at the US National Institute of Standards and Technology (NIST) just outside Washington DC, one of a number of metrologists working on a redefinition. The kilogram is the only fundamental unit of measure still defined by a physical object, he says.

The basic idea is to pin the kilogram to a precisely measured fundamental physical constant, in much the same way that the metre is now defined in terms of the speed of light in a vacuum: it's the distance that light travels in precisely 1⁄299,792,458 seconds. To do this for the kilogram would mean fixing Planck's constant, h, which reflects the size of energy quanta in quantum mechanics and is famously linked to energy through the frequency of light: $E = h\nu$. Combining that equation with the even more famous $E = mc^2$ then leads to a definition of mass.

Determining a precise value for Planck's constant is fussy work, however, and the two methods currently in favour disagree with each other enough to keep the redefinition of a kilogram on hold.

One of these ways makes use of a 'watt balance'. In essence this is a simple set of scales: on one side it has a 1-kilogram mass — standardized carefully against the one in Paris — and on the other it has a current-carrying coil of wire immersed in a magnetic field. The field is tweaked until the weight of the mass is balanced by the electromagnetic force on the coil, which can then be linked through a string of equations to Planck's constant. But in practice things are not that simple. Researchers still have to measure other things — the local gravitational field, for instance, the biggest source of error — and avoid any kind of vibration.

In 2007, a Watt balance now run by Pratt produced one of the most precise measurements of Planck's constant — $6.62606891 \times 10^{-34}$ J s, with a relative uncertainty of 36 parts per billion[2]. But another instrument, built at the National Physical Laboratory (NPL) in Teddington, UK, and now located at the National Research Council's Institute for National Measurement Standards in Ottawa, Canada, has yielded a result that differs from NIST's by an amount that is small, but just outside the experimental error[3].

The other favoured approach is to count the number of atoms in a sample of isotopically pure material. That would determine the value of the Avogadro constant — the number of atoms in exactly 12 grams of carbon-12, say — which can be linked mathematically to Planck's constant through another string of equations. In 2008, scientists at the Federal Institute of Physical and Technical Affairs in Braunschweig, Germany, began working with two near-perfect 1-kilogram spheres that had been fashioned from 99.995% pure silicon-28. Since then they have been using high-precision laser interferometry to determine the spheres' volumes, and X-ray diffraction to determine their crystal structures so that they can count the atoms with ever-more accuracy. So far they have measured the Avogadro constant as $6.02214082 \times 10^{23}$ with a relative uncertainty of just 30 parts per billion[4]. The translation of that into Planck's constant agrees with the NPL's watt-balance result, but not with the NIST's.

As of 2010, the recommended value for Planck's constant is $6.62606957 \times 10^{-34}$ J s, with an uncertainty of 44 parts per billion. Some say that's good enough to use to redefine a kilogram. But others want to keep picking away at it until the numbers agree better with each other and have a smaller range of error — to within 20 parts per billion.

That could take quite a while, says Pratt. "These are hard measurements to make. That's just the way it is." ■

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