EXOPLANETS ON THE CHEAP

The search for planets outside our Solar System will always be pricey. But creative solutions are proving that it no longer has to break the bank.

BY LEE BILLINGS

Astronomers searching for planets around stars other than the Sun have had much to celebrate over the past decade. The number of confirmed 'exoplanets' has soared from about 50 to more than 500 in that time. And although none of these planets closely resembles Earth, NASA's Kepler space telescope, launched in 2009, is now delivering candidates from distant stars by the hundreds — some of which may prove to be very Earth-like indeed (see page 24).

The exoplanet search itself has been wildly successful, but not so the searchers' quest for multibillion-dollar follow-up missions. Hopes for ambitious spacecraft such as a Space Interferometry Mission or Terrestrial Planet Finder have been dashed as missions have been cancelled or postponed owing to a combination of sluggish economic growth, deep cuts to space-science funding and programme difficulties with NASA's James Webb Space Telescope (JWST).

In response, the planet-hunting community has got creative, devising ways to maximize the science and minimize the costs. An Exoplanet Task Force jointly commissioned by NASA and the US National Science Foundation accordingly issued a report[1] in 2008, supporting a new strategy for exoplanet research. Rather than waiting for the launch of costly, dedicated planet-hunting spacecraft, it calls for astronomers to press ahead with cheaper, ground-based surveys to discover worlds orbiting nearby stars, which appear brighter to us than do those farther away, and so are easier to study. The hope is that such low-cost surveys will yield at least a few worlds that can be studied using space-based resources such as the JWST. Such facilities would allow astronomers to spectroscopically search the exoplanets' atmospheres for ingredients such as carbon dioxide, water vapour and perhaps methane, oxygen and other trace gases, which could indicate that life is present. A 2010 report from the European Space Agency reached nearly identical conclusions[2].

"The planets are out there, and it's relatively inexpensive to go after them," says Greg Laughlin, an astrophysicist at the University of California, Santa Cruz, who served on the NASA/National Science Foundation task force. "There's an economic inevitability to this."

Of the many ideas that astronomers have come up with for conducting exoplanet searches on the cheap, five stand out.

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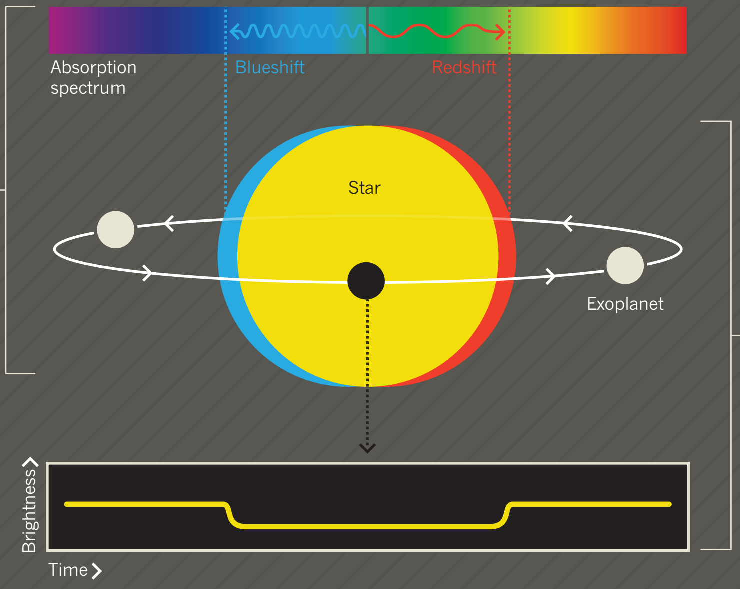
PLANET-HUNTING FOR BEGINNERS

Of the handful of techniques for finding exoplanets — planets orbiting stars other than our Sun — two are by far the most productive.

RADIAL VELOCITY

Radial velocity is the motion of a star caused by the gravitational influence of its orbiting planets. It can be measured through increases (blueshifts) or decreases (redshifts) in the frequency of light the star emits. Radial-velocity measurements can detect only planets whose orbits tug the star towards and away from the observer. The exact orbit of an exoplanet is hard to determine, so radial-velocity measurements let researchers deduce only the time a planet takes to orbit the star (its orbital period), how its orbit deviates from circular and its minimum mass. Radial velocity is most sensitive to massive planets with short orbital periods.



TRANSITS

When a planet crosses, or ‘transits’, the face of its star, it dims the star’s light by a small but detectable amount.
The probability that any planet’s transit will be visible from Earth is low, and is dictated by the ratio of the diameter of the star to the diameter of the planet’s orbit.
Large planets with short-period orbits of small stars are most likely to be seen transiting, and lots of stars must be surveyed for any transits to be found. Transits let researchers deduce the radius of a planet and its orbital period.
Astronomers can sometimes study a planet’s atmosphere as starlight filters through or reflects off it. This gives information on atmospheric composition, temperature and cloud formation.

M-DWARF TRANSIT SURVEYS (US$2 MILLION)

Central to the strategy is a focus on cool, red ‘M-dwarf’ stars close to the Solar System. Not only are there lots of them — M-dwarfs are the most abundant kind of star in the Milky Way — but they are much smaller and dimmer than the Sun, having less than half its mass. So any M-dwarf planet passing in front of the star, or ‘transiting’ it, would block a larger fraction of the light than it would of a larger star and would be easier to detect (see ‘Planet-hunting for beginners’). The comparative size of the transiting planet’s silhouette would also make it easier for telescopes to gather light filtering through its atmosphere for spectroscopic analysis.

The first, and so far most successful, search for potentially habitable planets transiting M-dwarfs is the MEarth Project (pronounced ‘mirth’): a cluster of eight 0.4-metre robotic telescopes at the Whipple Observatory on Mount Hopkins in Arizona. Unlike all previous transit surveys, which stare at a fixed patch of sky rich with stars, MEarth targets 2,000 nearby M-dwarfs; only if one of these displays a candidate transit will all telescopes observe it at once. The project is headed by David Charbonneau, an astronomer at Harvard University in Cambridge, Massachusetts, and was designed mainly by Philip Nutzman, now a postdoctoral researcher in astronomy at the University of California, Santa Cruz. MEarth announced the discovery of its first transiting planet in 2009 — a world dubbed GJ 1214 b, after the M-dwarf star it orbits some 13 parsecs from Earth[3]. The planet is too large and hot to harbour life as we know it, but was found in only the first six months of MEarth’s proposed three-year running time, and so far remains the most easily studied Earth-like exoplanet known. A spectroscopic study of GJ 1214 b, undertaken last year at the European Southern Observatory (ESO) in La Silla, Chile, showed that the planet’s upper atmosphere is either very hazy or is composed of water vapour[4].

“MEarth shows that for a relatively modest investment of US$1 million or $2 million, you can put together a ground-based survey capable of finding habitable-zone super-Earths,” says Charbonneau, referring to rocky planets that are larger than Earth and orbit their stars at a distance at which water can exist as a liquid. “The answer to the question being asked is certainly worth a lot more than that.”

By October 2011, Charbonneau and his colleagues hope to have a copy of MEarth operating in Chile, where it will see parts of the sky not visible from Arizona. Several other M-dwarf transit searches are also under way, notably at the 0.6-metre TRAPPIST telescope in La Silla, and at the 1.22-metre Samuel Oschin Telescope at Palomar Observatory in California.

NEAR-INFRARED SPECTROMETERS (US$5 MILLION)

Although transit observations are a good way to determine the radii and orbital periods of exoplanets, other techniques, such as spectroscopy, are essential for learning more.

Particularly important is the radial-velocity technique, the planet-hunting method that has produced the most hits so far. An orbiting planet tugs its star to and fro, generating periodic shifts in the wavelengths of the light the star emits; measurements of these shifts can not only allow independent confirmation of an exoplanet’s existence, but also provide estimates of its mass.

The method presents another good reason to focus on M-dwarfs. Earth’s motion around the Sun causes the star to wobble with a radial velocity of some 10 centimetres per second over the course of a year — a tough signal for any alien astronomers to detect. But if a planet the size of Earth were located in the habitable zone of an M-dwarf, much closer to the star, its radial-velocity signature would be a metre per second, much easier to see. Unfortunately, M-dwarfs shine most brightly with infrared and near-infrared light, so that is the region of the electromagnetic spectrum in which planet-hunters must search — but astronomers have yet to build the infrared spectrometers required for such precise measurements. So only a handful of the myriad M-dwarfs close to the Solar System have been surveyed for habitable planets.

Worse, planet-hunting near-infrared spectrometers are more costly than their optical counterparts, owing to basic physics: infrared photons don’t have enough energy to easily excite electrons in an off-the-shelf silicon detector. So the instruments rely instead on detectors made from expensive, exotic materials such as indium gallium arsenide or mercury cadmium telluride, and must be either cryogenically cooled or thermally insulated against background

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infrared radiation. The most cutting-edge near-infrared spectrometer is ESO's Cryogenic High-resolution Infrared Echelle Spectrograph (CRIRES), which cost some €10 million (US$13.6 million) to build.

Yet prices are dropping, and several major spectrometers may debut in the next few years, if they receive sufficient funding. Among them are the Calar Alto High-resolution Search for M-dwarfs with Exo-Earths with a Near-infrared Echelle Spectrograph (CARMENES), a German–Spanish instrument slated for the Calar Alto observatory in Spain; a near-infrared spectropolarimeter (SPIRou) on the Canada–France–Hawaii Telescope in Hawaii; and a US project, the Habitable Zone Planet Finder, slated for the Hobby-Eberly Telescope at the McDonald Observatory in Texas.

LASER FREQUENCY COMBS (US$100,000)

Another hurdle to the progress of M-dwarf planet discoveries is more subtle: the need for better ways to calibrate the spectrometers. The minuscule spectral-line shifts caused by an orbiting habitable planet can all too easily be mimicked by fluctuations in the stability of the instruments themselves. The obvious solution is to generate a reference spectrum with which the observations can always be compared. But the spectra generally used to calibrate optical radial-velocity surveys — those from iodine or a thorium–argon mix — don't produce usable calibration lines in infrared.

A number of other elements and mixtures are under investigation for calibration. But planet-hunters are most excited about an ultra-high-precision technology known as the laser frequency comb. At the core of such a device is a laser that emits rapid pulses that can be tuned across a wide range of wavelengths. Plotting the frequency of such a pulse train gives a distinct series of regular-wavelength peaks that resemble the teeth of a comb. When those pulses are fed through a spectrometer and synchronized with the ticking of an atomic clock, it becomes a powerful calibration source for spectroscopic measurements.

Efforts are under way to test laser combs on spectrometers at observatories. In late 2009 and early 2010, for example, a laser comb developed at the Harvard–Smithsonian Center for Astrophysics in Cambridge, Massachusetts, was linked to an optical spectrometer at the Whipple Observatory and used to calibrate spectroscopic measurements of a known planet-hosting binary star, HD 189733. In mid-2010, at the Hobby-Eberly Telescope, a comb developed at the US National Institute of Standards and Technology and mounted on a near-infrared spectrometer from the University of Pennsylvania, Philadelphia, obtained radial-velocity measurements of the planet-hosting star Upsilon Andromedae. And in December 2010, at ESO, a comb from the Max Planck Institute of Quantum Optics in Garching, Germany, made radial-velocity measurements of an exoplanet that were, for the first time, more accurate than the previous champion, thorium–argon calibration. The results of these tests are unpublished. If all goes well, combs from each team will grace next-generation spectrometers at major observatories in this decade.

> "THE PLANETS ARE OUT THERE, AND IT'S RELATIVELY INEXPENSIVE TO GO AFTER THEM."

RADIAL-VELOCITY OBSERVATORIES (US$50 MILLION)

Even armed with laser combs, planet-hunters could still be undone by the stars themselves, whose surface motions can masquerade as radial-velocity signals. "A star reverberates like a bell, with millions of modes of harmonic oscillations covering its surface, a bit like the weird patterns you get from putting sand on a vibrating drum head," says Steven Vogt, an astronomer at the University of California, Santa Cruz. "A few of these modes don't average out across the surface of the star, and they give you oscillations that can show up as noise in your observations."

The technique that has emerged to counter such noise sources is to average together 10–15-minute time-exposures of the star taken on consecutive nights over a period of weeks. Stéphane Udry, an astronomer at the University of Geneva in Switzerland, who hunts for planets at La Silla, says that it works. "We have a little sample of ten nearby stars we've begun following in this way, and we've already found planets around three of them," he says. "But a lot of observations are needed, because the stars are unlikely to have only one planet. So we have to cover all the potential periods for multiple planets, which takes time. As you try to make your measurements more precise, it quickly becomes expensive."

So expensive, in fact, that Vogt says the best way to reduce the long-term cost is to spend more money in the short-term on building radial-velocity-dedicated observatories. "The coin of the realm is observing nights," he says. "It's not new technology; it's not laser combs or some newfangled near-infrared spectrometers that can take advantage of M-dwarfs. Take $50 million, which is chump change in the NASA regime, build a 6–8-metre telescope with enough light-gathering power to reach a large fraction of the nearest M-dwarfs, put a nice spectrometer on it and dedicate it to this work every single night of the year. You'd have these planets pouring out of the sky."

Vogt and his colleagues have built a demonstration project, the Automated Planet Finder (APF): a 2.4-metre robotic telescope paired with a high-efficiency spectrometer at Lick Observatory on Mount Hamilton, California. The APF, according to Vogt, is "built and bred only to find short-period rocky planets" around nearby stars, including the brightest M-dwarfs in the sky. The project is now in its final installation phase, with commissioning scheduled for this month. Vogt expects it to rapidly discover a bevy of small, rocky worlds.

EXOPLANETSATS (US$250,000 EACH)

Radial velocity's most important role in the future may be helping to verify and study promising transit discoveries. "Transit searches are the most advantageous technique giving access to terrestrial planets in the habitable zones of stars," says Udry. "We cannot beat that."

Astronomers are already brainstorming successors to the Kepler mission, which would carry out transit surveys of nearby stars looking for worlds with the potential for life. In the meantime, a much cheaper proposal is the ExoplanetSat programme being developed by Sara Seager, an astronomer at Massachusetts Institute of Technology in Cambridge, and her team. The idea is to build on the existing framework for 'CubeSats' — miniaturized satellites, made up of varying numbers of cubes 10 centimetres on each side, designed to hitch low-cost rides into orbit on rockets launching larger spacecraft. Seager's plan calls for a fleet of dozens of CubeSats, each targeting an individual star and containing a small telescope and guidance equipment. Outside Earth's atmosphere, which interferes with observations, such a payload could detect transiting Earth-sized planets in the habitable zones of nearby Sun-like stars.

Seager admits that engineering such 'nano-satellites' to have the necessary stability and thermal control will be challenging. But she and her team hope to launch a functional prototype as early as 2012, with subsequent satellites launching for as little as $250,000 apiece — a bargain-basement price for a space-science mission. "On one hand, this seems risky because the probability of finding a transiting Earth-sized planet in the habitable zone of a nearby star is currently estimated at 1 in 200," she says. "On the other, these satellites are modular and relatively cheap; launching one has low risks and what may be very high returns. Basically, this could be MEarth in the sky." ■ SEE EDITORIAL P.5

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1. The Exoplanet Task Force *Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets* (NASA Astronomy and Astrophysics Advisory Committee, 2008).
2. Exoplanet Roadmap Advisory Team *A European Roadmap for Exoplanets* (ESA, 2010).
3. Charbonneau, D. *et al. Nature* **462,** 891–894 (2009).
4. Bean, J. L., Kempton, E. M.-R. & Homeier, D. *et al. Nature* **468,** 669–672 (2010).

GENOMICS

Gene reading steps up a gear

Third-generation sequencing machines promise to make their mark one molecule at a time.

BY HEIDI LEDFORD

IN A FLASH

New DNA sequencers watch an enzyme called DNA polymerase as it uses fluorescently tagged bases to synthesize DNA. Each base is identified by a distinguishing colour that flashes as the base is incorporated into the DNA strand.

"It's super cool, but it's never going to work," genomics guru Eric Schadt responded when a wary investor asked for his opinion about a new DNA-sequencing technology in 2003. A company was creating a machine that it claimed could revolutionize the field by reading over the shoulder of an enzyme as it copied DNA molecules.

Despite his initial scepticism, Schadt touted the method's success last weekend at the Advances in Genome Biology and Technology meeting in Marco Island, Florida. Now chief scientific officer at the company he had once doubted — Pacific Biosciences in Menlo Park, California — Schadt was one of several researchers at the meeting who provided a glimpse of how the company's first DNA-sequencing machines are performing.

All eyes are on these machines. Pacific Biosciences set a high bar for its own success in 2008, when chief technology officer Stephen Turner boasted that the instruments would be able to sequence a human genome in just 15 minutes by 2013, compared with the full month it took at that time. This year, as researchers unveiled data from the first machines to leave the company's campus, the discussion was less about revolutionizing the field and more about niche applications.

After several delays, customers have now been told to expect their machines in the second quarter of this year.

The machines potentially offer advantages over the 'next-generation' sequencers currently on the market. Users of the new machines last week reported generating sequences an average of 1,500 base pairs long — about ten times the length of those currently produced by the state-of-the-art sequencers from Illumina in San Diego, California. These longer reads make it easier to stitch fragments of DNA sequences together into a coherent genome sequence.

"Single molecule is the future of sequencing, but it still has hurdles."

Pacific Biosciences' machines are also fast. In a paper published online in December, Schadt and his team used them to trace the origin of the ongoing cholera outbreak in Haiti by sequencing the genomes of five strains of *Vibrio cholerae* (C. S. Chin *et al. N. Engl. J. Med.* **364,** 33–42; 2011). The team sequenced all five strains in less than an hour. It takes about a week to complete a 150-base sequencing run on an Illumina sequencer.

But for many researchers, the key advance of the Pacific Biosciences machines is the ability to sequence single molecules of DNA. The instruments work by watching as an enzyme confined within a tiny compartment copies DNA, adding fluorescently labelled bases that flash with characteristic colour as they are added to the DNA strand (see 'In a flash'). Leading sequencers on the market instead report an average sequence taken from a population of molecules.

Single-molecule sequencing opens the door to analysing rare sequence variants, and frees researchers from having to amplify DNA samples before sequencing — a step that can introduce errors, and can fail altogether for certain DNA sequences. "Single molecule is the future of sequencing," says Michael Metzker, who studies sequencing technology at Baylor College of Medicine in Houston, Texas. "But it still has hurdles."

Chief among those hurdles has been high error rates. Whereas other methods on the market surpass 99% accuracy, users of the Pacific Biosciences machines last week reported an accuracy rate of about 85%. Schadt argues that this can be overcome by resequencing the same molecule repeatedly.

Nevertheless, because of the cost of its machines (US$700,000 per unit compared with less than $125,000 for the new Illumina sequencer rolling out this autumn) and limits on the number of sequences that can be read during every run, the instruments are unlikely to disrupt the sequencing market in the near future. For now, the machines are likely to be used for tackling regions of the human genome that resisted conventional sequencing. The instruments can also detect some chemical modifications to DNA, which could be useful to the burgeoning epigenetics field. Peter White, who heads the sequencing centre at Nationwide Children's Hospital in Columbus, Ohio, says he is interested in acquiring a machine, but would mainly use it to analyse microbial genomes, which tend to be much smaller than mammalian genomes.

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At the meeting last week, Turner did not reiterate his pledge for a 15-minute human genome. But he did emphasize that there is still plenty of room for the current instrument to improve. "We are just at the beginning of this technology." ■

CORRECTIONS

The News story 'Social science lines up its biggest challenges' (*Nature* **470,** 18–19; 2011) should have said that Nick Nash did his MBA at Stanford University.

The News Feature 'Exoplanets on the cheap' (*Nature* **470,** 27–29; 2011) should have said that the spectrometer on which the comb at the Hobby-Eberly Telescope was mounted came from Pennsylvania State University not the University of Pennsylvania.

The graph in the News Feature 'The End of the Wild' (*Nature* **469,** 150–152; 2011) showing a correlation between rising minimum temperatures in Wyoming and increased survival rates for mountain pine beetles should have made it clear that the beetle data were modelled not measured.