▲ In the past decade, the floodgates have opened on extrasolar planet discoveries; worlds perhaps like the ringed gas giant illustrated here

DETLEV VAN RAVENSWAAY/SPL

Strange new worlds

There are now over 150 planets outside the Solar System known to science. **Hazel Muir** reports on the quest to find Earth's twin

By anyone's reckoning, the past decade has been a glorious one for planet hunters. Before the 1990s, we were completely in the dark about whether any planets existed around stars beyond the Sun. But since 1995, strange new alien planets have popped up right, left and centre.

Astronomers have found more than 150 extrasolar planets already, and that's just the tip of the iceberg – the Milky Way is probably teeming with planets just waiting to be discovered. Many of the newfound worlds are incredibly strange. Some are gas giants just a stone's throw from their stars, their atmospheres fizzling into space as they roast in the heat. Some planets swing wildly through their host systems like grossly overgrown comets. One even navigates the gravitational minefield of a triple star system where it shouldn't even exist.

It would be far-fetched to imagine that life evolved on these hostile worlds. But astronomers hope to detect cosy, rocky planets just like Earth over the next ►

Planet hunting

▸ two decades. Finally, it might be possible to answer an ancient question: do any other planets host life?

Philosophers have speculated about planets beyond this Sun for thousands of years, but it was only in the 20th century that astronomers started to look for them in earnest. They knew telescopes couldn't image planets circling other stars directly, because they would be too dim. But if a heavy planet like Jupiter was orbiting a star, its gravity might make the star 'wobble' a little. In the 1960s, an astronomer claimed to have seen these telltale wobbles in a nearby star – Barnard's Star in the constellation Ophiuchus – but it turned out to be a false alarm. By 1990, still with no planets to report, planet hunters wondered despondently if extrasolar planets were very rare indeed.

Closely guarded secert

But exactly 10 years ago, in October 1995, things changed dramatically when astronomers Michel Mayor and Didier Queloz from the Geneva Observatory in Switzerland revealed a secret they'd been guarding for months. They'd discovered a planet circling a star called 51 Pegasi, about 50 lightyears away. What's more, this planet was an absloutely extraordinary world, nothing like what any of the planet hunters expected to find.

Mayor and Queloz had used a telescope in France to monitor around 150 nearby stars. They hoped to detect any wobbling of these stars by looking for subtle changes in their spectra due to the so-called 'Doppler effect'. If a star is moving towards us, its spectral lines should become compressed and slightly more blue and, conversely, more stretched out and red as the star moves away. Measuring the period of this cycle could reveal the orbital period of an unseen planet, while the size of the wobble would indicate the planet's mass.

By late 1995, Mayor and Queloz became convinced that they were seeing this signal from 51 Pegasi. The star's wobble indicated that it had a planet roughly half as massive as Jupiter in tow. But oddly, the planet lay astonishingly close to its parent star. While the giant planets in our Solar System orbit the cool outer regions, the new planet was closer to its star than Mercury is to the Sun, and whipped round it in just four Earth days. How could a giant, Jupiter-like ball of gas survive so close to its star?

They announced the finding in October 1995, and the news hit the headlines around the world. The planet was quickly confirmed by Geoff Marcy of San Francisco State University and Paul Butler from the University of California at Berkeley, who had been searching for planets at Lick Observatory in California since 1987. Marcy and Butler had a backlog of data, and now they trawled through it to see if they could find other planets like the one circling 51 Pegasi. The following January, they reported two new giant planets – one orbiting 70 Virginis and the other orbiting 47 Ursae Majoris.

The floodgates had opened, and new planets came in thick and fast. Today, more than 150 planets have been discovered, the majority of them by Marcy and Butler's team. About 20 of these extrasolar planets are in multiple systems with two, three or four planets, while the rest are lone planets, as far as astronomers can tell.

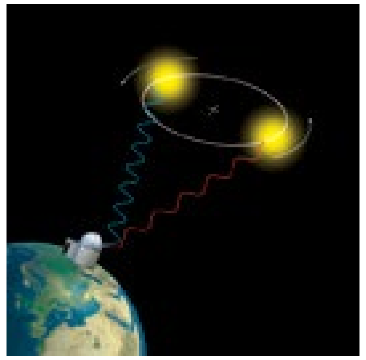
The curious giant planet circling round 51 Pegasi has turned out to be far from unique. Some 20 of all the extrasolar planets are similar 'hot Jupiters', lying less that 0.1 astronomical units away from their stars (one astronomical unit is the mean distance from the Earth to the Sun).

Shaking up theory

The hot Jupiters have really shaken up theories about how planets form. Until the 1990s, astronomers based their theories of planetary formation only on our Solar System, where we see a clear pattern. The four inner planets – Mercury, Venus, Earth and Mars – are small and rocky, while the gas and ice giants (Jupiter, Saturn, Uranus and Neptune) lie in a deep freeze more than five astronomical units from the Sun. Theory suggested that all the planets formed within a dusty disk of gas that surrounded the young Sun. Dust particles clumped together in the heat of the young star to make rocky planets. But the giants had to form much further out, where it was cool enough for them to trap vast blankets of gas and ice.

So seeing hot Jupiters baking in three-day orbits was a shock. Astronomers now think that the hot ▸

[DISCOVERY **METHOD #1**]

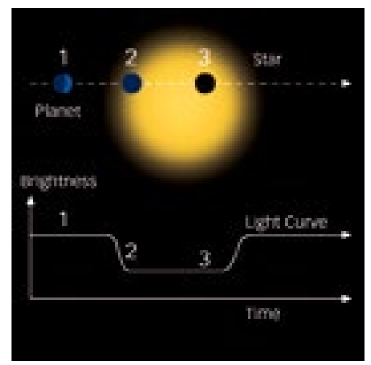


WOBBLING STARS

The vast majority of extrasolar planets detected so far have been spotted because their gravity makes their parent stars wobble. If a star has a single planet circling it every 30 days, the star will follow a smaller circle every 30 days too. Astronomers can measure the star's wobble by looking at specific wavelengths of starlight – the light becomes more blue as the star moves towards us, and more red as it moves away, an effect called the Doppler shift. Measuring this movement back and forth reveals the planet's orbital period and minimum mass.

▲ **The Lick Observatory telescope in California was used by Marcy and Butler to find extrasolar planets**

[DISCOVERY **METHOD #2**]



TRANSITS

If a planet crosses in front of a star, as viewed from Earth, it can be detected because it periodically blocks out some light from its star, making it dimmer. Astronomers can then measure the diameter of the planet from the amount of starlight it blocks. It's also sometimes possible to probe the starlight flooding through the backlit planet's atmosphere to see what elements are inside. The drawback of studying transiting planets is that they are rare – only seven have been seen to date. That's because the plane of a planet's orbit must be precisely edge-on when viewed from Earth. But the nice thing about transits of extrasolar planets is that you don't need a world-class telescope to see them.

[TYPES OF EXTRASOLAR PLANET]

[Hot Jupiters]

Of more than 150 extrasolar planets found so far, around 20 are classed as hot Jupiters – gas giants orbiting amazingly close to their stars, at less than a tenth of the Earth-Sun distance. That means their year lasts about 10 Earth days or less. Astronomers think these gas giants usually formed far away from their parent stars but soon migrated towards the star. That could happen because a dusty disk of gas around the star sapped the planet's angular momentum, or because the disk material swirled onto the star and dragged the planet with it.

[Super-Earths]

The four lightest planets found so far have been called 'super-Earths'. Actually, three of them have masses more like that of Neptune, around 21, 18 and 15 times that of the Earth. However, these planets have a very different environment to Neptune, because they whip round their stars in 10 days or less. In June, astronomers announced the lightest planet found so far – a seven-Earth-mass planet. No one is sure what these planets are like, but astronomers speculate that the lightest is a rocky planet with about twice the diameter of the Earth.

[Free-floating planets]

Astronomers have seen signs of lightweight bodies, a bit heavier than Jupiter, floating around without any parent stars. In 2000, British astronomers reported seeing a dozen of these planetary orphans in the Trapezium star cluster in Orion. Theoretical models that calculate the mass of the objects from their brightness and temperature suggested they have masses five to 13 times that of Jupiter. However, they might be failed stars called brown dwarfs, and many astronomers argue that without a parent star, these objects shouldn't be called planets anyway.

[Pulsar planets]

It's possible for planets to orbit a pulsar, a type of neutron star. These can form when an ordinary star blasts apart in a supernova, leaving behind a super-dense core. One pulsar called PSR B1257+12 in the constellation Virgo appears to have at least three worlds circling round it, two of them about four times as massive as Earth and one a bit larger than the Moon. Astronomers think the planets formed after the star turned into a pulsar, around a billion years ago. They speculate that the planets are rich in heavy elements like iron and have strong magnetic fields.

[Ordinary giants]

At least one extrasolar planet looks reassuringly familiar; like Jupiter it has a sedate orbit. The planet is about four times as massive as Jupiter, and takes 14 years to orbit its star, 55 Cancri. The likelihood is that long-period giant planets are common, but it takes a while to find them. To confirm a long-period planet, astronomers have to patiently monitor its parent star's wobbles during a whole planetary orbit, taking more than a decade. Because the hunt for extrasolar planets only got going in earnest in 1995, it will take some time to compile a census of long-period planets.

PAUL WOOTTON X2; MEL LINDSTROM/SPL; NASA/GSFC; CHRIS BUTLER/SPL; ESA; NASA/JPL-CALTECH/R HURT (SSC-CALTECH):

Planet hunting

▸ Jupiters probably formed in cold regions far away from their stars. Then they later migrated inwards, due to some kind of interaction with a dusty disk of gas that surrounded the parent star when it was young. Friction between the giants and the disk could have sapped their orbital angular momentum and made them spiral inwards, ever closer to their stars.

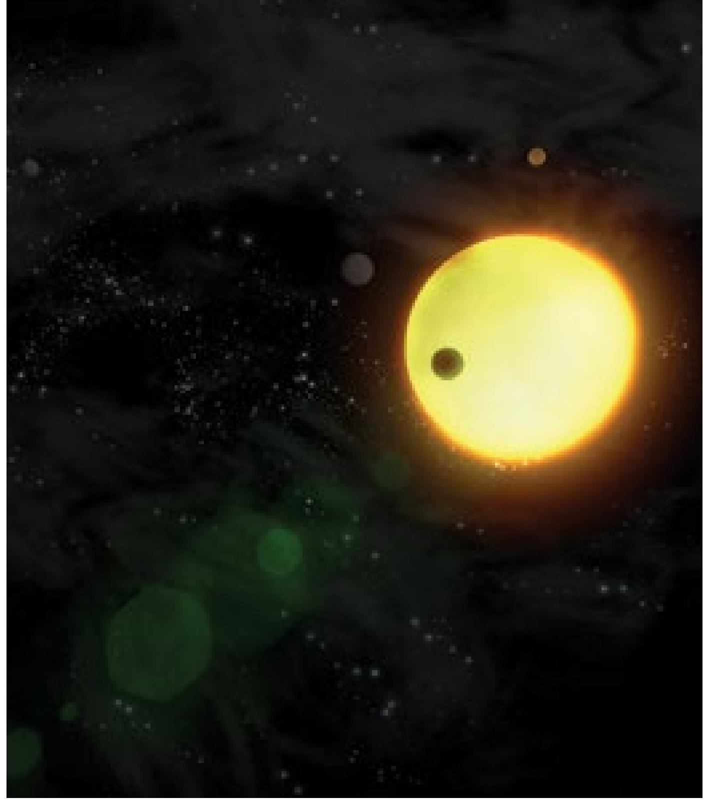
There's another puzzling difference between the familiar planets of the Solar System and the 150-plus exoplanets. About nine out of 10 exoplanets have 'eccentric' orbits that are much more elongated and elliptical than the fairly circular orbits typical of our own planets. An extreme example is a four-Jupiter-mass planet orbiting a star called HD 80606. The planet comes as close as 5 million km (3 million miles) to its star, then swings out to 127 million km (79 million miles) away. Gravitational interactions between different planets are thought to have amplified their 'swing'.

One of the most exciting planet finds came in 1999, when Tim Brown of the National Center for Atmospheric Research in Colorado and his colleague David Charbonneau were trying out a new planet-spotting technique. They reasoned that a small fraction of extrasolar planets must happen to orbit exactly edge-on to the line of sight from Earth. In that case, they could cross the star's face once during each orbit. Brown and Charbonneau hoped to measure the slight dimming of a star's light when a planet crosses or 'transits' its star.

Car park discovery

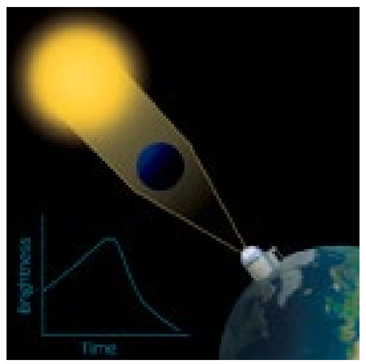
To detect the dimming, they developed a telescope system called STARE to monitor thousands of stars at once. In late 1999, when they were just testing the STARE equipment in a car park, Brown and Charbonneau struck gold. They monitored a star called HD 209458, 150 lightyears away in the constellation Pegasus, and saw the shadow of a 0.7-Jupiter-mass planet moving across the star every three-and-a-half days.

The amount of starlight it blocked allowed astronomers to measure the diameter of an exoplanet directly for the first time. Despite being less massive than Jupiter, its diameter turned out to be 35 per cent bigger. It's not clear why the planet is quite so bloated, although it's probably partly to do with the intense heat from the nearby ▸



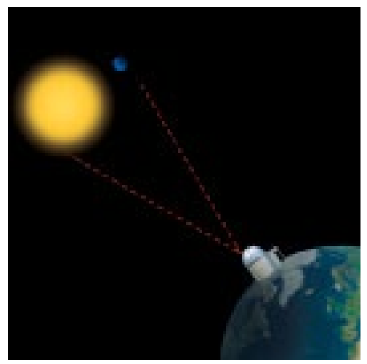
▲As identification techniques get more sophisticated, astronomers expect to find smaller exoplanets

[DISCOVERY **METHOD #3**]



MICROLENSING
If one star passes in front of another, as viewed from Earth, the gravity of the nearer one bends the light from the background star, briefly magnifying it. If the nearer 'lens' star has a planet in orbit around it, the magnification shows a characteristic pattern. So far, this method has revealed two exoplanets.

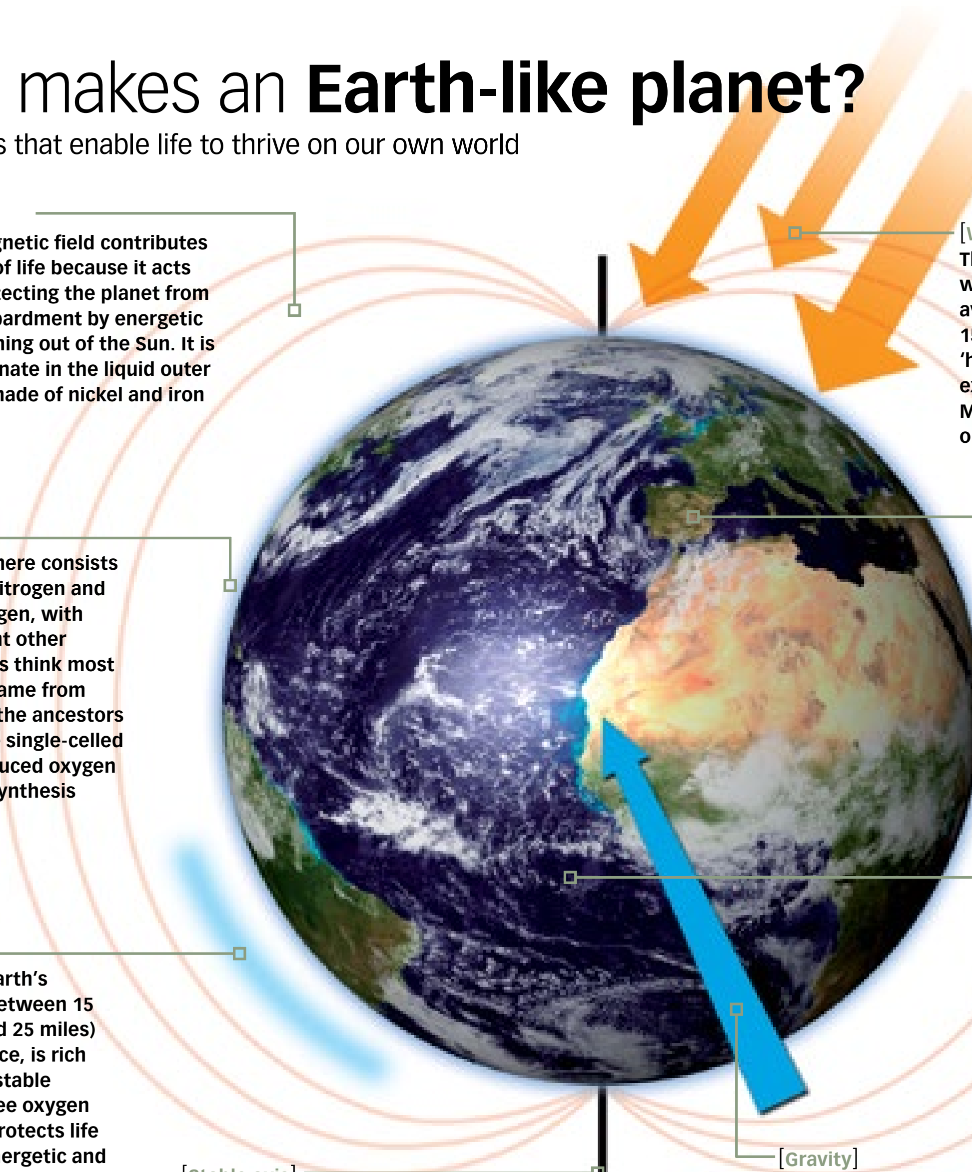
[DISCOVERY **METHOD #4**]



DIRECT IMAGING
This is very difficult because the planets are dim and hard to see in the glare of the light from the parent star. But using the Very Large Telescope in Chile, astronomers have captured an image that may show a planet, roughly five times as massive as Jupiter, orbiting a brown dwarf about 230 lightyears away.

What makes an **Earth-like planet?**

Eight factors that enable life to thrive on our own world



[Magnetic field]
The Earth's magnetic field contributes to the success of life because it acts as a shield, protecting the planet from damaging bombardment by energetic particles streaming out of the Sun. It is thought to originate in the liquid outer core, which is made of nickel and iron

[Warm climate]
The Earth has a hospitable climate, with the Sun's rays giving it an average surface temperature of 15°C (59°F). It lies within the 'habitable zone' of our Solar System, extending roughly from Venus to Mars, where liquid water could exist on a planet's surface

[Atmosphere]
Earth's atmosphere consists of 78 per cent nitrogen and 21 per cent oxygen, with just one per cent other gases. Scientists think most of the oxygen came from cyanobacteria, the ancestors of plants. These single-celled organisms produced oxygen through photosynthesis

[Rocky surface]
To be like Earth, a planet must have a rocky surface. That means it should be much smaller than the gas giant Jupiter. Gas giants are so massive that they trap light gases like hydrogen and helium, and they have no distinct surface.

[Surface water]
About 70 per cent of the Earth's surface is covered with water. Because life as we know it – from people to plants and bacteria – is made chiefly of water and dependent on it to survive, it's difficult to imagine a dry world being habitable

[Ozone]
A layer of the Earth's stratosphere, between 15 and 40km (9 and 25 miles) above the surface, is rich in ozone, an unstable molecule of three oxygen atoms. Ozone protects life by absorbing energetic and harmful ultraviolet radiation from the Sun

[Stable axis]
The Earth has a stable axis of rotation, which has kept its climate fairly uniform and allowed the evolution of life. The gravity of our large Moon is responsible for this. Without the Moon, the Earth's spin axis would wobble chaotically

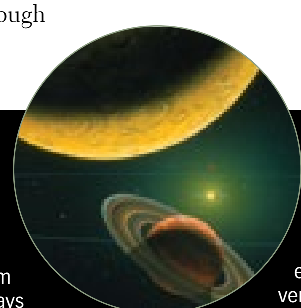
[Gravity]
The Earth's gravity traps a hefty atmosphere around the planet, some five thousand billion tonnes of gas. Any Earth-like planet must be significantly more massive than the Moon, which has no permanent atmosphere because its surface gravity is just a sixth of the Earth's

[The planet hunter]

Paul Butler is a leading planet hunter at the Carnegie Institution of Washington in Washington DC

What was planet-hunting like back in the early days?
When Geoff Marcy and I started this programme in September 1986, there were no known extrasolar planets. To proclaim oneself a 'planet hunter' had about the same cachet as claiming to be a paranormal researcher or 'ufologist'. From June 1987, we gathered stellar spectra with the Lick Observatory's 3m telescope, and tried to find ways of converting that data into precise velocities to reveal the presence of planets. But we were groping around in the dark for years, and ended up going down innumerable blind alleys in our search.

How did you find your first planet?
After the discovery of a planet by Michel Mayor and Didier Queloz in October 1995, we borrowed extra computers and I began a crash programme to analyse our backlog of data. The first two planets emerged in December 1995. The second of these was an eight-Jupiter-mass behemoth in a very elliptical, eccentric orbit. Prior to its discovery we would never have imagined seeing something like that.

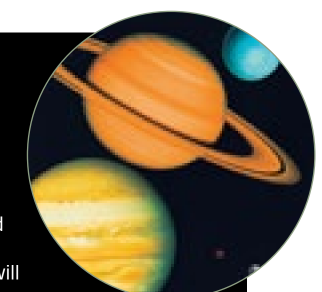


What has been the biggest highlight in almost 20 years of planet hunting?
I think the biggest highlight has been watching the discipline grow from being ridiculed for 50 years of false detections and predictions into a major and exciting new branch of astrophysics.

What finding has surprised you most?
What's most surprising is the extraordinary diversity of planetary systems. It is now common knowledge that most other planetary systems have highly eccentric orbits, and that Jovian planets are commonly found in three-day orbits. Back in 1996 and 1997, these were stunning and controversial developments, but it now appears that our own Solar System is in fact the odd one out in the zoo of planetary formation.

What discovery do you most look forward to?
The discoveries that are most delightful are complete surprises. In their immediate wake we are befuddled and cannot understand what is staring us in the face; as though our very senses have been scrambled. They remind us that human imagination is very limited indeed.

Do you think Earth-like, habitable planets are common?
Earth-sized planets are probably common, and I suspect that there are probably lots of planets inhabited by simple creatures like single-celled organisms. But more complex creatures are probably rare, and the kind of creatures that are capable of technological development must be very rare indeed.



When will we find Earth-like planets?
Within the next 10 years, I would expect that the existing precision Doppler groups will begin to find small, rocky planets in very small orbits. This will be our first hint of just how many Earth-like planets might exist out there.
On the slightly further horizon, I would estimate in 10 to 20 years time, programmes like the NASA Space Interferometry Mission (SIM) could find the first rocky planets in Earth-like orbits

▸ star that is making the planet's atmosphere expand.

In total, seven transiting planets have been found to date. One of them, announced earlier this year, circles a Sun-like star called HD 149026 every 2.88 days. It has roughly the same mass as Saturn, but its diameter is much smaller, so the planet is clearly very dense. The observations make most sense if this 'hot Saturn' contains lots of heavy elements in a solid core about 70 times as massive as the Earth.

Dramatic sunrises

Another baffling world made its debut in July. Maciej Konacki of the California Institute of Technology discovered it using the 10m Keck I telescope in Hawaii. The planet is in a triple-star system called HD 188753, about 150 lightyears away. It orbits a Sun-like star every 3.35 days, while two further stars circle the pair at roughly the distance between Saturn and the Sun. The giant planet must witness dramatic triple sunrises of a white, an orange and a red star.

No one knows how a planet could have formed in this system. The gravity of the two outer stars should have swept away the raw materials for planet building. Astronomers hope to find more planets in multiple star systems to clarify what kind of extreme conditions a growing planet can tolerate.

Extrasolar planets as lightweight as the Earth have not been detected around any normal stars. Until now, planet-hunting technology has not been sensitive enough to detect the subtle wobbles that small terrestrial planets induce in Sun-like stars. But that looks set to change. Both NASA and the European Space Agency are planning orbiting space observatories to start hunting for alien Earths either this decade or the next.

These observatories should reveal hundreds of Earth-sized planets. The next big challenge will be to find out if any of these planets can host life. That's easier said than done. But a good starting point might be to scan the new worlds for water and oxygen molecules, says Butler: "If a space-based telescope were capable of imaging a tiny Earth-like planet and obtaining a spectrum capable of resolving water vapour, ozone, methane, and carbon dioxide in my lifetime, I would be delighted."

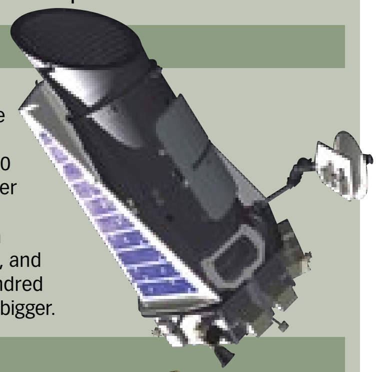
Astronomers also hope to resolve another mystery – can 'free-floating planets' exist? There have been several reports that planet-mass objects wander around young star clusters, apparently without any parent stars. It's possible that their masses have been underestimated, and they are in fact heavier, failed stars called brown dwarfs. But even if they are just a little heavier than Jupiter, can they be called planets when they don't circle a star? The issue is already a bone of contention among planet hunters.

The debate shows just how much can change in a decade. Astronomers are now facing new worlds beyond their wildest dreams, worlds that challenge our very understanding of the word 'planet' itself. ✪

[The new seekers]

Both NASA and the European Space Agency are planning a series of future missions with the aim of finding out more about exoplanets

[Kepler: 2008]



NASA plans to launch a 0.95m (3ft) diameter space telescope to constantly monitor more than 100,000 stars simultaneously. Kepler will spot tiny changes in a star's brightness when a planet passes in front of it, and could discover several hundred planets the size of Earth or bigger.

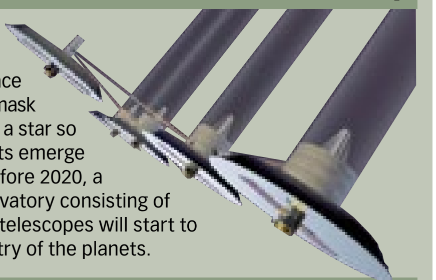
[Gaia: 2011]

Gaia is a European Space Agency (ESA) mission aiming to measure the positions of a billion stars in the Milky Way. It could also detect as many as 50,000 Jupiter-mass planets because their gravity would make their stars wobble from side to side.

[SIM PlanetQuest: 2011]

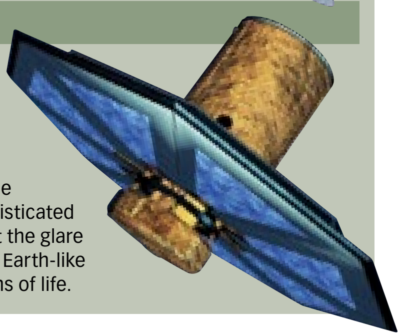
This NASA mission will launch a series of telescopes mounted on a boom 10m (33ft) long. The observatory will measure the positions of stars extremely precisely, and could uncover planets just slightly bigger than the Earth by looking for stars wobbling sideways.

[Terrestrial Planet Finder: 2014 and 2020]



NASA's TPF mission will start with an optical space telescope using a mask to block light from a star so that nearby planets emerge from the glare. Before 2020, a second TPF observatory consisting of a fleet of infrared telescopes will start to probe the chemistry of the planets.

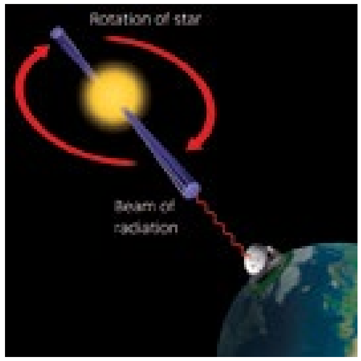
[Darwin: 2015]



ESA plans to launch a family of three infrared space telescopes with a fourth spacecraft to act as a communications hub. The telescopes will use sophisticated techniques to cancel out the glare of stars, then scan faint, Earth-like planets for chemical signs of life.

NASA X3; ESA X2; PAUL WOOTTON

[DISCOVERY **METHOD #5**]



PULSAR TIMING

Planets have been discovered around two pulsars – spinning neutron stars that emit polar radio beams. These sweep across the Earth like lighthouse beams hundreds of times each second, allowing radio telescopes to measure regular radio beeps. Irregularities in the beep rate can signal the presence of a planet whose gravity tugs the neutron star back and forth. This technique is extremely sensitive and can detect objects as small as asteroids.

ON THE COVERDISC
Watch Patrick Moore and guests debate the prospect of alien life, and see a gas giant orbit a triple star system

[FIND OUT MORE]

http://exoplanets.org/
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***Infinite Worlds*, Ray Villard and Lynette R Cook, University of California Press, 2005**