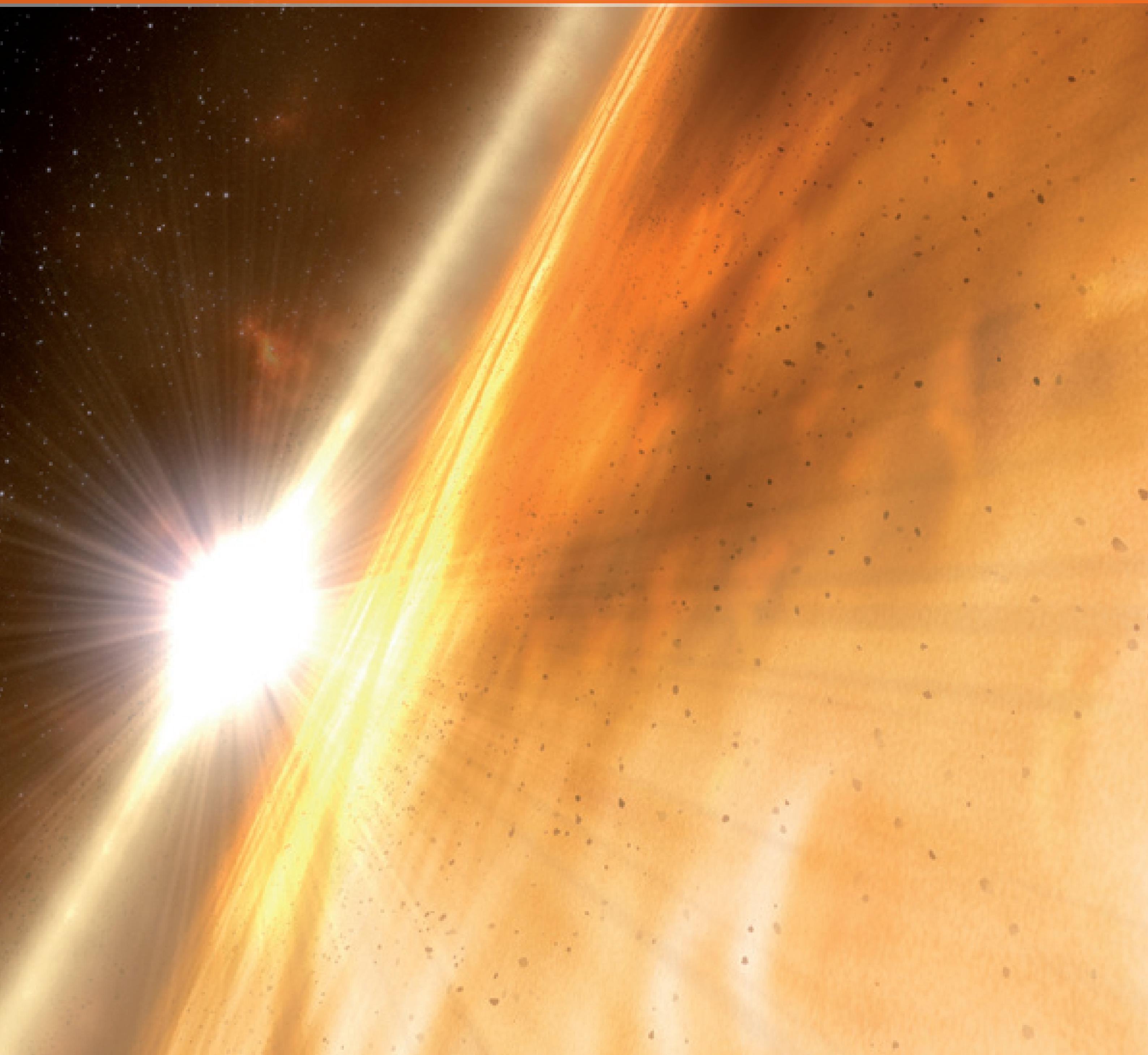
EXOPLANETS

The search for planets beyond our solar system



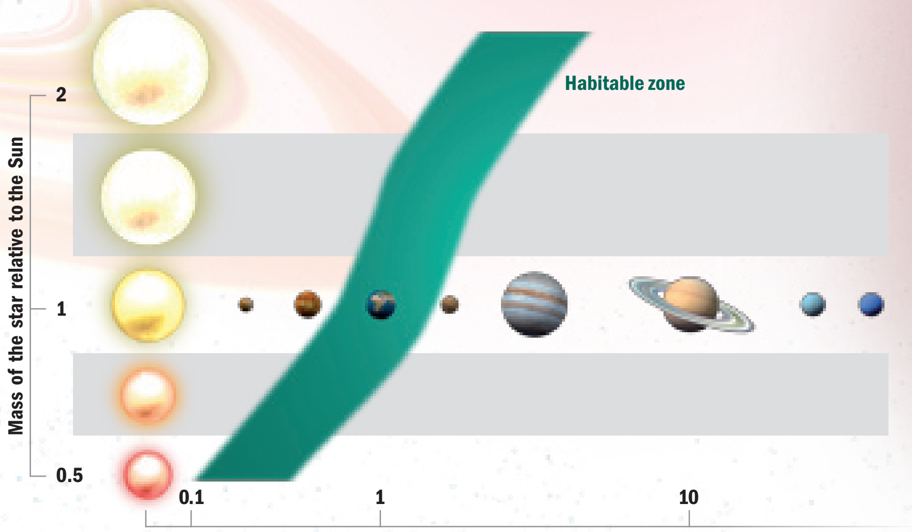
IOP Institute of Physics

People have long wondered if other solar systems like ours exist with planets capable of supporting life. The discovery of truly Earth-like planets would revolutionise our understanding of our place in the universe. Until recently, the science and technology to detect exoplanets did not exist. However, in the past two decades, astronomers have developed new techniques and instruments that are providing growing observational evidence that our home galaxy – the Milky Way – is rich with planetary systems. Scientists estimate that of its 100 billion stars, more than 10 billion could host planetary systems, with at least 10 per cent of Sun-like stars having planets.

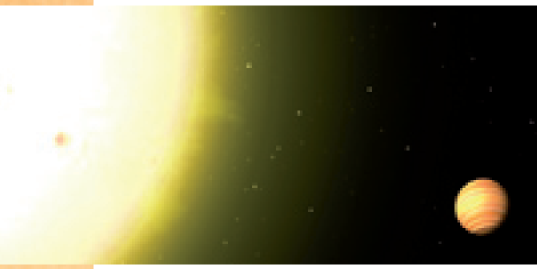
THE DISCOVERY AND STUDY OF PLANETS ORBITING STARS OTHER THAN OUR SUN – EXOPLANETS – IS ONE OF THE MOST EXCITING SCIENTIFIC CHALLENGES FOR THE 21ST CENTURY

A NEW FRONTIER FOR HUMANKIND

More than 400 exoplanets have been discovered to date (2010). The number is rising rapidly, as astronomers around the world sift through huge amounts of observational data from ground-based telescopes and dedicated space missions. In the coming years, the number will rise to thousands. Although most of the exoplanets found so far have been the size of the gas and ice giants in our solar system – Jupiter, Saturn, Uranus and Neptune – future generations of instruments and observatories may enable researchers to image directly small, rocky planets like Earth orbiting distant Sun-like stars, and analyse their atmospheres for tell-tale signs of life. Such searches represent the next frontier for scientific exploration – following in the footsteps of Galileo and Darwin in past centuries.



Variation of the location of a star's habitable zone (where liquid water can exist) with the star's mass


The first of the 'hot Jupiters', 51 Pegasi b

THE EARLY DISCOVERIES

The first exoplanets, discovered in 1991, orbited a pulsar – a neutron star emitting regular pulses of radio waves. Then in 1995, Michel Mayor and Didier Queloz of the University of Geneva in Switzerland, using the Haute-Provence Observatory in France, uncovered the first exoplanet around a normal Sun-like star, 51 Pegasi b, which is 50 light years from Earth. The planet is about half the size of Jupiter and whirls around its star in just over four days. Being at a distance that would be inside the orbit of Mercury in our solar system, 51 Pegasi b has a temperature of 1500K. It became the first of the so-called 'hot Jupiters', which account for the majority of exoplanets since discovered.

The late 1990s saw the field explode, revealing a rich variety of planets. In 1996, US planet-hunters Geoffrey Marcy of the University of California, Berkeley and Paul Butler of the Carnegie Institution of Washington discovered three more Jupiter-like planets: 70 Virginis b, which has an extremely eccentric orbit; Tau Boötis b, a searingly hot Jupiter orbiting at a distance that is less than one-seventh of Mercury's from the Sun; and 47 Ursae Majoris b, a cooler gas giant orbiting further away from its parent star. The first multiple-planet system containing three Jupiter-like planets orbiting at different inclinations (unlike our coplanar solar system) was also identified orbiting the star Upsilon Andromedae, and in 1998, Gliese 876 b, the first planet orbiting a red dwarf star, was found. This Jupiter-sized world resides in the star's so-called habitable zone – the distance from the star at which water would remain liquid and thus support life. The red dwarf, Gliese 876, was later found to harbour two more inner planets, one of which could be a large version of Earth. An exoplanet orbiting the yellow dwarf star of the binary system, 55 Cancri, discovered at the same time, was later found to have at least four companion planets. The era of exoplanet discovery had truly begun.

HOW TO FIND AN EXOPLANET

A star outshines any of its planets (which emit mainly reflected starlight) by a factor of between a million and a billion, so discovering a distant exoplanet might seem impossible. However, astronomers have used their deep understanding of physics combined with sophisticated instrumentation and data analysis to tease out the signals indicating the presence of a planet. The UK has several teams of astronomers that are making major contributions, and also supports leading international planet searches through its subscriptions to the European Southern Observatory (ESO), the European Space Agency (ESA) and the Gemini telescopes.

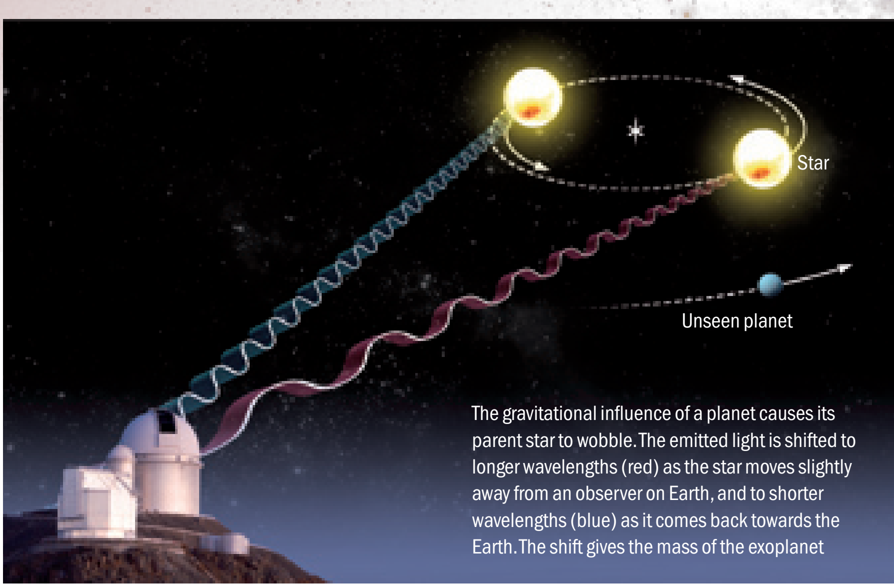
A gas giant planet in the habitable zone of the red dwarf Gliese 876

RADIAL VELOCITY MEASUREMENTS

The first exoplanets were discovered through the gravitational tug they exert on their parent stars, which causes the stars to wobble. This motion is revealed in the spectrum of a star's emitted light. Elements present in the star absorb particular wavelengths of light to produce a characteristic set of spectral lines, which are then are minutely shifted back and forth as the star moves. The so-called radial velocity (RV) method works best in identifying high-mass planets close to their stars, and gives a lower limit on the planet's mass relative to the mass of the star. This means that the less mass a star has, the more easy it is to see the effects of a smaller planet. For this reason, planet-hunters are especially interested in red dwarfs, which are extremely common and which have habitable zones that are much closer in than for a Sun-like, G-type star.

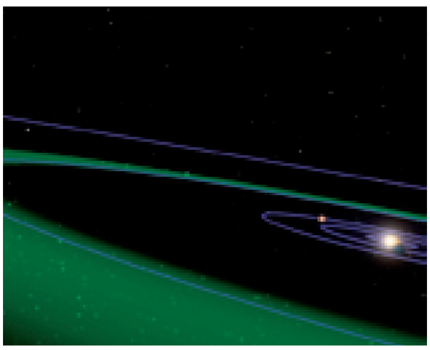
UK INVOLVEMENT

The first measurements used relatively small telescopes (just over a metre in diameter) but with high-quality spectrographs. Roger Griffin at the University of Cambridge first developed a spectrograph suitable for detecting planets in the 1970s. UK astronomers, including Hugh Jones of the University of Hertfordshire, have led the **Anglo-Australian Planet Search** on the 3.9-metre Anglo-Australian Telescope in Australia, using the University College London Echelle Spectrograph (UCLES). This ongoing survey of 250 nearby stars has been running since 1998 and has found 35 exoplanets. The team is now looking for smaller planets similar to Earth, as well as genuine Jupiter analogues around Sun-like stars.

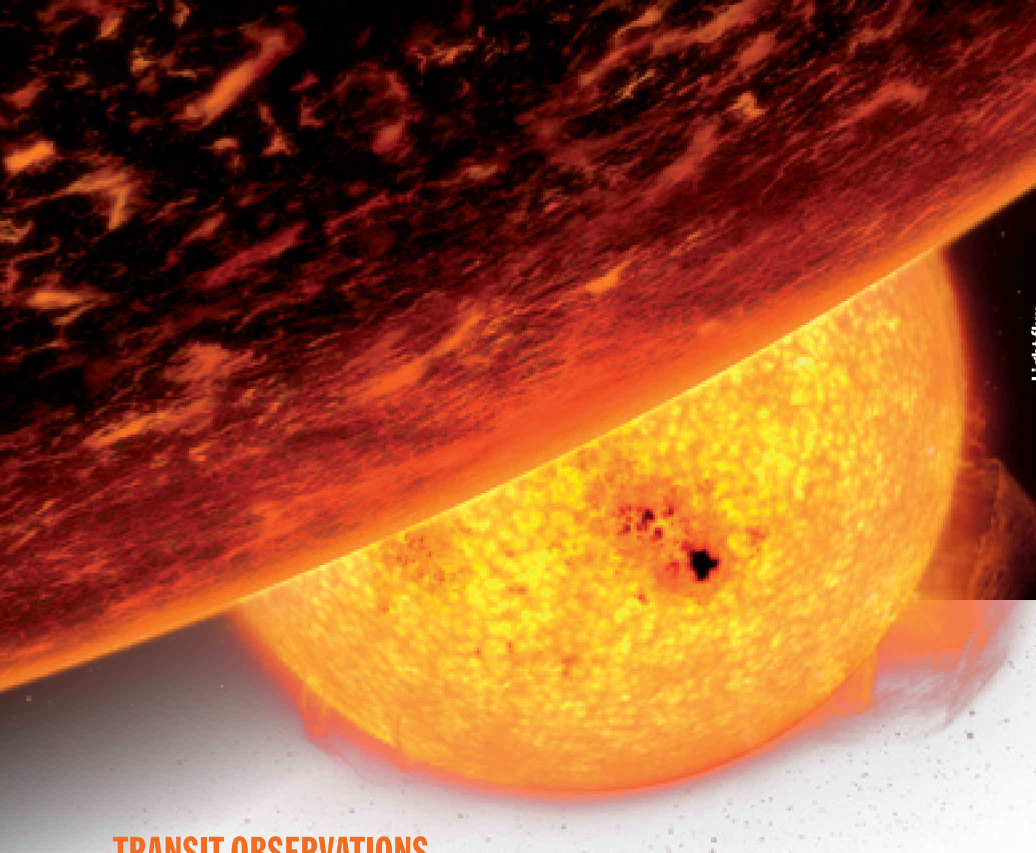


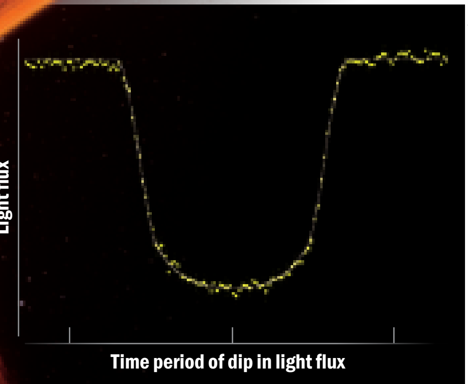
The gravitational influence of a planet causes its parent star to wobble. The emitted light is shifted to longer wavelengths (red) as the star moves slightly away from an observer on Earth, and to shorter wavelengths (blue) as it comes back towards the Earth. The shift gives the mass of the exoplanet

ESO's main planet search is carried out with the **HARPS** spectrograph on its 3.6-metre telescope in Chile, with a new instrument, **HARPS-North**, being installed on the William Herschel Telescope (WHT) on La Palma in the Canary Islands. HARPS searches have uncovered an abundance of systems, some containing Neptune-size and lower-mass planets, including the lightest-known exoplanet Gliese 581 e, which is only twice the mass of Earth and sits well within the star's habitable zone. Another instrument, a near-infrared spectrograph on the ESO's Very Large Telescope (VLT) array in Chile, called **CRIRES**, is searching for planets around cool red dwarfs.


NASA/JPL-Caltech

The binary system, 55 Cancri, has five known planets





The dip in light from the star COROT 7 revealed a small planet, COROT 7 b

ESO/L. Calcada

TRANSIT OBSERVATIONS

Exoplanets are also detected by measuring the dimming of a star's brightness as a planet passes in front. The planet's orbital plane must lie close to the line of sight to the star. Transit measurements allow the planet size to be calculated but require follow-up RV measurements to work out the mass. The first transit planet, HD 209458 b, which is 150 light years from Earth, was found in 1999. Follow-up spectroscopic studies in 2004 with the **Hubble Space Telescope (HST)** and NASA's **Spitzer** infrared space telescope revealed it has an atmosphere containing hydrogen, carbon, oxygen, and sodium.

UK INVOLVEMENT

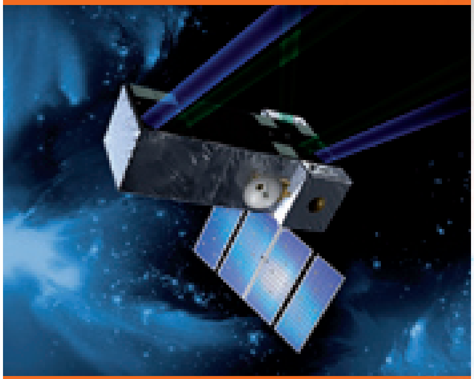
UK researchers have been involved in analysing data from the HST and Spitzer telescopes. In 2007, Giovanna Tinetti of University College London (UCL) and colleagues reported results on the atmosphere of exoplanet HD 189733 b. This planet had first been discovered, via the transit method, using the ELODIE radial velocity spectrograph on the 1.9-metre telescope at the Haute-Provence Observatory. Being 30 times closer to its star than the Earth is to the Sun, the bloated gas planet is held in a tight gravitational grip so that one side always faces the star. The researchers showed that the scorching hot atmosphere contains molecules of water, carbon dioxide and methane, and they are now exploring the similar atmospheres of two other 'hot Jupiters'.

The UK's main exoplanet search employs a battery of dedicated cameras working robotically. A consortium of eight institutions, represented by Don Pollacco of Queen's University Belfast (QUB), is operating the world's most successful transit survey, the Wide Angle Search for Planets (**SuperWASP**) project. Two observatories, designed to cover both hemispheres – SuperWASP-North on the Isaac Newton Group of Telescopes on La Palma, and SuperWASP-South at the South African Astronomical Observatory – each consisting of eight wide-angle cameras (with CCD detectors made by Andor Technology, a spin-out company from QUB), simultaneously survey the sky, monitoring millions of stars for transit events. Since starting in 2004, the project has already uncovered evidence for up to 30 new exoplanets. Another European project, the **WFCAM Transit Survey**, led by David Pinfield at the University of Hertfordshire, uses the wide-field camera on the UK Infra-Red Telescope (UKIRT) on Hawaii to search for planetary transits across red dwarfs.

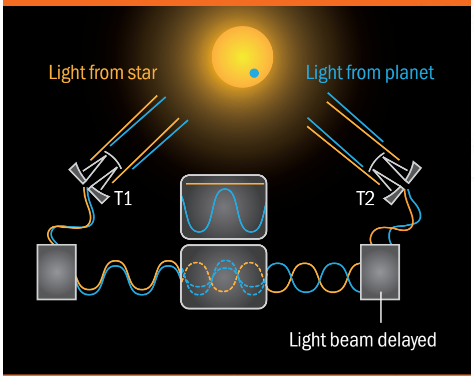
Transit searches are also being carried out from space. In 2006, ESA and the French national space agency launched the **COROT** mission. Its 27-centimetre telescope, with CCDs made by the electronics company e2v in Essex, has found the smallest planet to date, COROT 7 b, which is only twice the size of Earth and of similar density. Suzanne Aigrain and Frédéric Pont at the University of Exeter are part of the European team that analyses the transmitted data and then carries out follow-up observations using ground-based instruments. In 2009, NASA launched a larger, 95-centimetre telescope, **Kepler**, to look at 100 000 Sun-like stars in the hope of finding Earth-like planets.

DETECTING EXOMOONS

David Kipping at UCL has calculated that NASA's Kepler mission could discover habitable moons orbiting large exoplanets by detecting the tiny gravitational wobble they cause in transiting planets



The SIM Lite Astrometric Observatory



The principle of nulling interferometry

NULLING INTERFEROMETRY

Interferometry, whereby light waves received by several telescopes are combined to give a proportionately higher-resolution image, is a technique of growing importance in astronomical observations. The technique was pioneered in radioastronomy at the University of Cambridge and is now being applied to optical telescopes. It can be used to find exoplanets because the light signals received by each telescope from the star can be combined so that the waves cancel out, leaving just the image of the orbiting planets.

UK INVOLVEMENT

The two telescopes of the W. M. Keck Observatory on Hawaii already use nulling interferometry, and ESO and ESA are developing a new instrument called **GENIE** to be used on the VLT interferometer array.

The Gaia spacecraft

ASTROMETRY

Another significant tool in detecting exoplanets is to measure directly the periodic displacement of a star's position on the sky caused by a planet's gravitational pull.

UK INVOLVEMENT

ESA's mission **Gaia**, to be launched in 2011, will aim at uncovering many thousands of planets within about 650 light years of the Sun, using both the transit and astrometric methods. UK university groups are participating in the **Gaia Data Processing and Analysis Consortium (DPAC)** to analyse the light from millions of stars that Gaia will map.

At the same time, ESO is building a highly accurate astrometric instrument, **PRIMA**, to be installed on one of the four telescopes of the VLT array, which will be able to detect exoplanets.

Preparing for the installation of the astrometric instrument PRIMA on the VLT

The four telescopes of ESO's VLT

POLARIMETRY

A method of characterising the atmosphere of hot Jupiters is to detect directly the reflected light from the planet, which can be distinguished from the star's light, because it is fractionally polarised (the planes of the reflected light waves are oriented in the same plane).

UK INVOLVEMENT

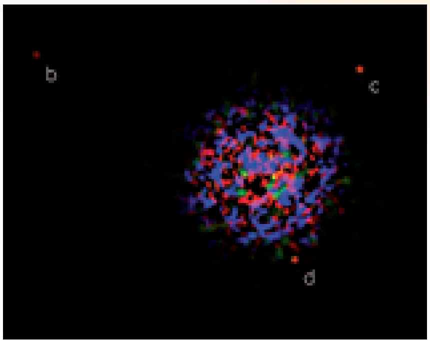
Jim Hough and his team at the University of Hertfordshire designed and built a highly sensitive polarimeter, **PlanetPol**, for use on the WHT. A version of this pioneering device is being incorporated into a new instrument for the VLT, **SPHERE**, along with advanced adaptive optics, coronagraphs and an infrared camera spectrograph. It will study new exoplanets orbiting nearby stars by direct imaging of their circumstellar environment.

DIRECT DETECTION

New technology is allowing astronomers to detect directly the visible and infrared light from giant planets in wide orbits, similar to those in our solar system.

UK INVOLVEMENT

The first such images were obtained in 2008. Direct images of three giant planets orbiting the nearby, young star HR 8799 were taken by an international team, including Jenny Patience at the University of Exeter. Each planet is larger than Jupiter and the orbits range in size from within the Sun-Neptune distance to that lying outside the orbit of the dwarf planet Pluto. There may be smaller rocky planets in closer orbits, and future observations will search for terrestrial planets in this system.

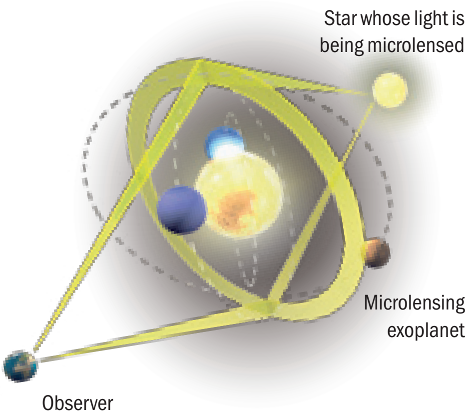


A direct image, taken by the W. M. Keck Observatory, showing the three planets of HR 8799 (b, c, and d). The coloured speckles in the centre are the remains of the bright light from their parent star after image processing

At the same time, a second team, using the HST, found a giant planet on the inner edge of the huge dust ring which was already known to surround a hot young star, Fomalhaut, 25 light years away from Earth. The observations were taken with an instrument called a coronagraph, which uses a disc to block out the otherwise blinding light from the star. The UK has been heavily involved in preparations for observing with a new, highly advanced adaptive optics/coronagraph system, the **Gemini Planet Imager (GPI)**, which will be installed in Gemini-South in 2011. It will enable vastly more sensitive searches for fainter planets in closer orbits.

MICROLENSING

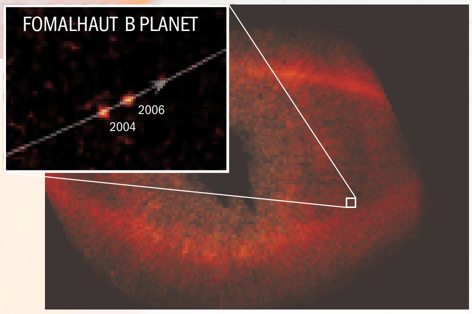
Astronomers are good at finding ingenious ways of exploiting the laws of nature to explore the universe. Einstein showed that a gravitational field acts like a lens in bending the path of light. The astonishing effects are seen in the distorted multiple images of distant galaxies. This phenomenon also leads to the brightening of a star, say, deep in the central bulge of the Milky Way, by a foreground (possibly invisible) 'microlensing' star close to its line of sight from Earth. Any planets around this star, when in the right position, will produce a sudden increase or decease in the brightening. Microlensing is more sensitive to low-mass planets than other methods, and can reveal even those at Earth-mass scales. The lensing stars are most likely to be far from Earth in the galactic bulge, and the planets themselves cool objects in orbits far from their parent stars. Microlensing thus offers a complementary technique to the RV and transit methods, which detect large, nearby planets.



Light reaching us from a distant star is bent and focused by the gravity of an intervening planetary system, causing the star to vary in brightness as a planet passes in front

UK INVOLVEMENT

UK groups work within a network of worldwide microlensing programmes, **OGLE**, **MOA** and **PLANET**. Also included are observations with the UK's network of robotic telescopes, **RoboNet-1.0**, led by Keith Horne at the University of St Andrews. In 2005, the RoboNet ream discovered OGLE-2005-BLG-390L b, which, at five times the Earth's mass, was the first cool, 'super-Earth' to be found.



NASA/ESA and P. Kalas (University of California, Berkeley)

The Fomalhaut system as seen with the HST. The planet Fomalhaut b orbits the young star every 872 years

UNDERSTANDING STARS AND PLANETS

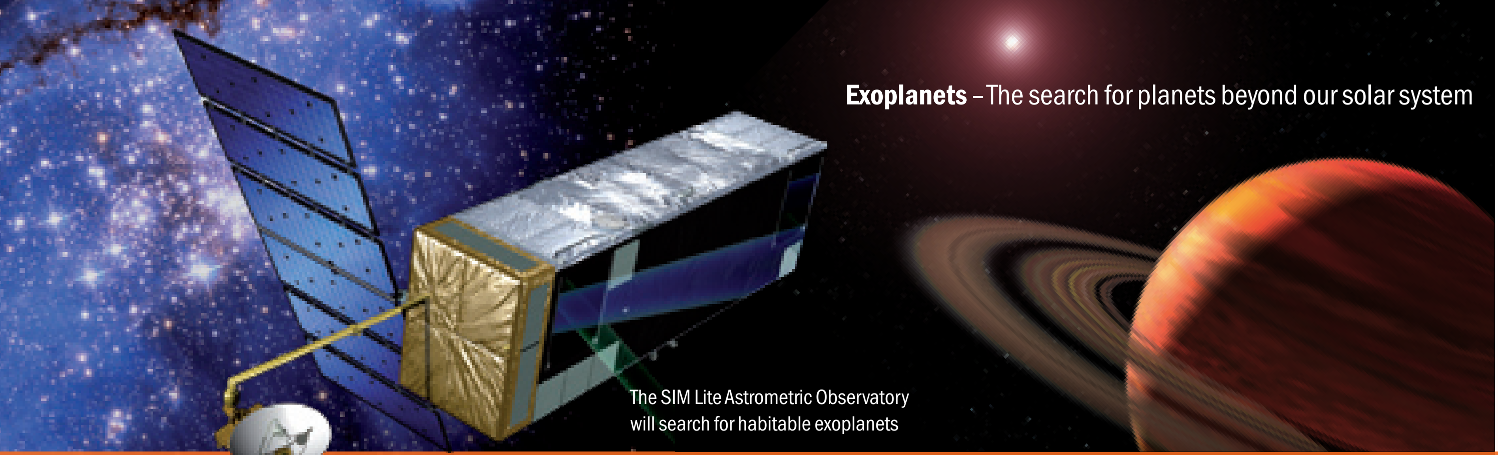
The extraordinary range of worlds found have already got theorists re-working their ideas about the evolution of planetary systems. How do monster planets end up orbiting so closely to their star? Planetary systems are thought to condense from the dust disc that surrounds a young star, and one idea is that these Jupiter-size planets spiral in from the outer reaches, through interactions with the congealing circumstellar material. They could also form through the mergers of smaller planets.
One goal now is to search for and study protoplanetary systems (like Fomalhaut's). Future projects and missions will survey systems, with the aim of building up a picture of planetary-system architecture and composition in relation to the evolution and behaviour of the different star types. Several UK theory groups are using supercomputers to model planet formation in discs.

UNDERSTANDING OUR WORLD

Exoplanet research will give us a better understanding of planetary evolution, and thus of our own world. Studies by geologists and atmospheric scientists of exoplanetary environments will provide useful data that will inform current concerns about our changing planetary environment.

SEARCHING FOR OTHER EARTHS

The discovery of habitable, truly Earth-like planets would be one of the most exciting and significant events in human history. The detection of atmospheric gases such as ozone could indicate that an exoplanet might harbour life.



Exoplanets – The search for planets beyond our solar system

The SIM Lite Astrometric Observatory will search for habitable exoplanets

A NEW SCIENCE IS DAWNING

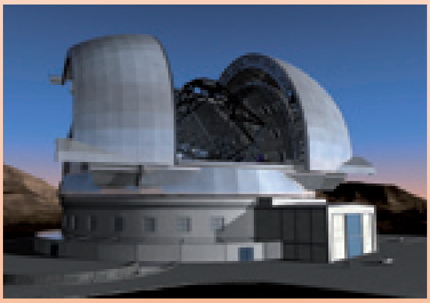
THE BURGEONING FIELD OF EXOPLANETOLOGY INVOLVES THE COMPARATIVE STUDY OF EXOPLANETS – THEIR FORMATION, GEOLOGY AND ATMOSPHERES

FUTURE PROJECTS

The discovery of so many planets in just a few years offers a tantalising taste of how our galaxy could be explored with new technology and instruments.

New ground-based telescopes and instruments are being planned. A next-generation spectrograph **ESPRESSO** for the VLT, to find rocky planets, is on the drawing board, and the ESO **European Extremely Large Telescope (E-ELT)**, which at 42 metres will be the world's biggest telescope, will track down Earth-like planets in habitable zones and investigate the chemistry of young, evolving systems. Antarctica, which offers continuous observing in the winter, could provide an ideal environment for exoplanet observations, and new telescope projects based there have been proposed.

In space, Hubble's successor, the **James Webb Space Telescope (JWST)**, will provide images and spectra of exoplanets, and very young planetary systems. A potential addition is NASA's **New Worlds Mission**, which would involve placing a large petal-shaped disc to block a star's light so that its planets are more easily seen. ESA is considering a further mission, **PLATO**, to look for habitable-zone planets around nearby stars, while NASA is looking at a mission, **THESIS**, which would study the atmospheres of transiting exoplanets that orbit in a host-system's habitable zone.



The European Extremely Large Telescope

Both ESA and NASA have considered more ambitious missions, **Darwin** and the **Terrestrial Planet Finder**, in which several space telescopes work as an interferometer by flying in formation. They have the potential to observe Earth-like planets directly.

However, because of the enormous technical challenges – and budgetary restraints – they have been postponed. In the meantime, NASA is developing a two-instrument interferometer, the **SIM Lite Astrometric Observatory**, to make astrometric measurements of nearby stars for evidence of habitable Earth-mass planets.

The UK is already participating in some of these projects – the E-ELT and the JWST among them. Dr Tinetti is a member of ESA's Exo-Planet Roadmap Advisory Team (EPRAT), which is advising ESA on how to move towards the ultimate goal of detecting biomarkers (signatures of life) on habitable exoplanets. Dr Pont is a member of the JWST science team sub-panel that focuses on optimising the capability of JWST for exoplanet observations, and Professor Pollacco is the science principal investigator of PLATO. The instrumentation group at the University of Oxford, led by Niranjan Thatte, is involved in preliminary studies for the E-ELT's direct imaging instrument, **EPICS**. However, there are further decisions to be made as to how far the UK wishes to support this important area of discovery.

Thanks go to Suzanne Aigrain and Jenny Patience at the University of Exeter, Hugh Jones and Jim Hough at the University of Hertfordshire, Keith Horne at the University of St Andrews, Don Pollacco of QUB and Giovanna Tinetti of UCL for their help with this paper. The UK has a number of world-leading research groups expert in various aspects of exoplanet science (theoretical modelling of formation, geology and atmospheres) as well as detection techniques and instrument development, not all of whom could be mentioned in this paper.

Useful websites

The Extrasolar Planets Encyclopaedia http://exoplanet.eu

Planet Quest Exoplanet Exploration http://planetquest.jpl.nasa.gov

California Planet Search http://exoplanets.org

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