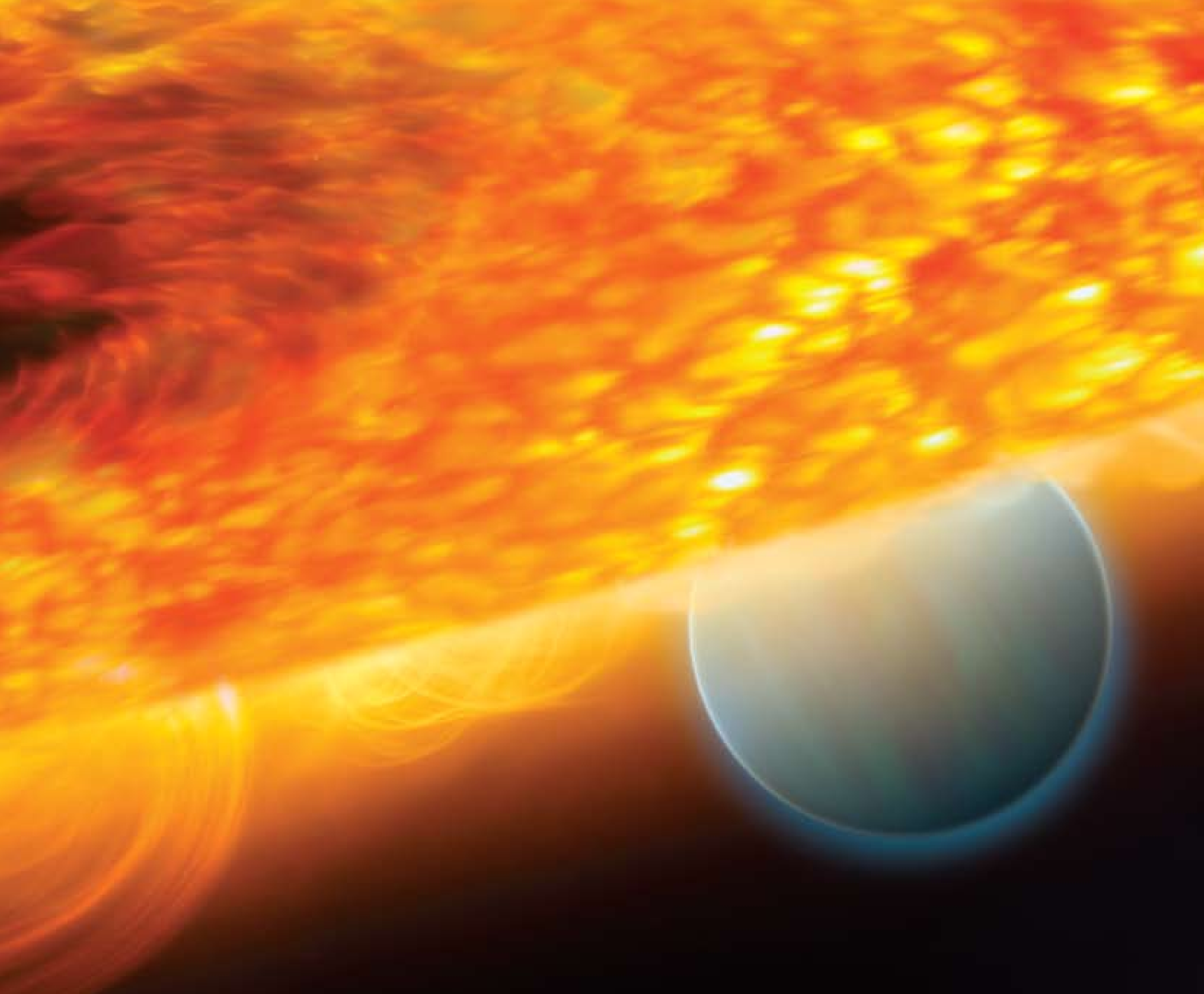
EXTRASOLAR PLANETS

Information for the Media



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Preface

Since planets were first discovered outside our own Solar System in 1992 (around a pulsar) and in 1995 (around a "normal" star), extrasolar planet studies have become one of the most dynamic research fields in astronomy. Our knowledge of extrasolar planets has grown immensely, from our understanding of their formation and evolution to the development of different methods to detect them.

This guide provides an overview of the history of extrasolar planets and of the current state of knowledge in this captivating field. It reveals the various methods that astronomers use to find new exoplanets and the information that can be inferred. The last section summarises the impressive findings of extrasolar planet research at ESO and the current and near-future technologies available in the quest for new worlds.

Cover: *Artist's impression of the extrasolar planet HD 189733b | ESA, NASA, G. Tinetti (University College London, UK & ESA) and M. Kornmesser (ESO)*

Left: *Artist's impression of an extrasolar planet orbiting its star | ESA, NASA, M. Kornmesser (ESO) and STScI*

1 Early Discoveries

"There is an infinite number of worlds, some like this world, others unlike it"

EPICURUS-LETTER TO HERODOTUS (~300 B.C.)

A planet is an object orbiting a star, massive enough to have achieved an almost spherical shape and to have cleared the protoplanetary disc where it was born of dust and debris. They differ in this from dwarf planets (such as Pluto), which do not have enough mass to clear the protoplanetary disc area.

The first detection of an extrasolar planet occurred in 1992 when the astrophysicists Aleksander Wolszczan and Dale Frail discovered three extrasolar planets. They were found in an unexpected environment, orbiting the pulsar PSR1257+12.

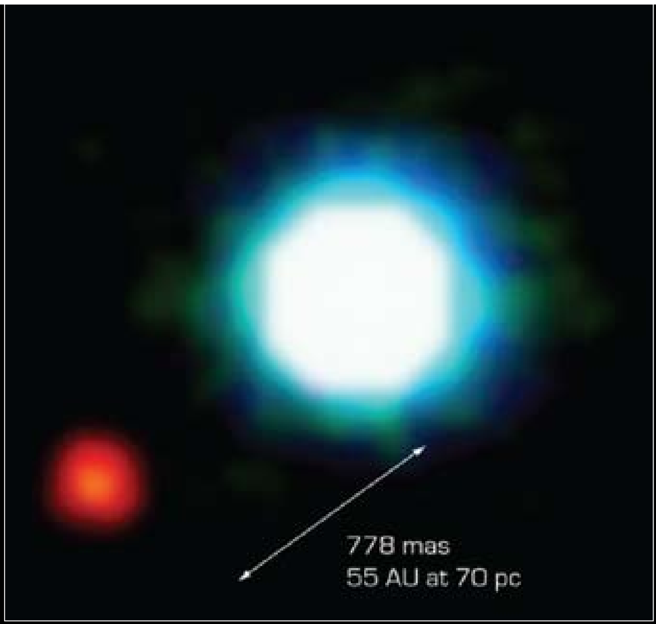
In 1995, the Geneva-based astronomers Michel Mayor and Didier Queloz detected the first extrasolar planet around a "normal" (main sequence) star, 51 Pegasi. The planet, named 51 Pegasi b, has around half the mass of Jupiter and whizzes around its parent star in just over four Earth days, lying almost eight times closer to it than Mercury is to the Sun.

Since 1995, this area of astronomy has become a very dynamic research field and astronomers have found over 350 extrasolar planets (as of April 2009), using a host of techniques.

Left: *ESO 3.6-m telescope, La Silla Observatory | ESO*

Right: *La Silla Observatory | ESO*

Artist's impression of the planetary system around HD 69830 | ESO



Possibly the first image of an exo-planet (red spot), obtained with NACO at the VLT. The planet orbits a brown dwarf (blue spot in middle). ESO

Techniques for Detection 2

Searching for extrasolar planets is like looking for the proverbial needle in a haystack. Planets emit little or no light of their own, while their host stars shine brightly. Seeing the light from a distant planet is like spotting a dim candle in front of a raging forest fire.

Nowadays six investigative tools are used to spot hidden extrasolar planets.

- *Direct detection*
  1. Imaging
- *Indirect detection*
  2. Radial velocity
  3. Astrometry
  4. Pulsar Timing
  5. Transits
  6. Gravitational Microlensing

Direct Detection

Imaging

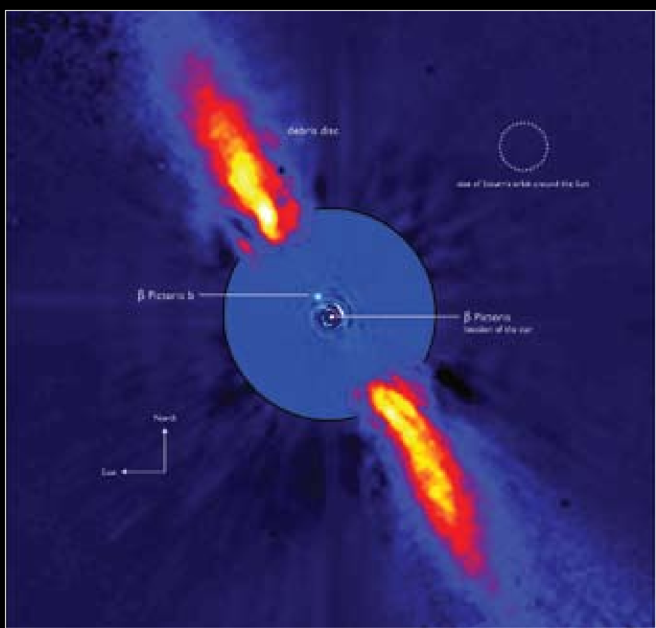
The hardest way to detect an extrasolar planet is to try to image it directly. This is because of the extreme contrast between the light emitted by the parent star and by the companion planet. To expose the planet, the starlight must be dimmed or masked in some way so as to enable observers to see into the shadow. One method is to use infrared radiation, rather than visible light. The visible light output of a Jupiter-like planet is one billionth of that of its host star, while in the infrared the contrast is just a few thousandths. This is particularly true when the planet is still very young and thus contracting, thereby emitting heat. Another method is to physically block out the starlight, using a coronograph that masks the bright central core of the star, leaving only the corona, the outer plasma region of the star's atmosphere, visible and so allowing nearby planets to shine through.

Direct imaging is the only way to assess some important physical parameters, such as the amount of water on the surface and the properties of any possible biosphere. The Adaptive Optics NACO instrument on the Very Large Telescope has obtained the first image of an exoplanet. The European Extremely Large Telescope, planned for 2018, will search for new planets using direct imaging, thanks to its very sharp vision.

Indirect Detection

The majority of all extrasolar planets discovered so far have been detected using indirect methods — identifying their existence by their effect on their host star.

The presence of a planet affects its host star in several ways. The weak gravity of the planet pulls the star in a small circular orbit, introducing a minute wobble that can be detected using radial velocity tracking or astrometry (see pages 8-10). Alternatively, as the planet moves between the star and the observer, the measured luminosity of the star will change. These tiny variations are important for astronomers, as it makes the indirect observation of extrasolar planets possible.



Beta Pictoris as seen in infrared light | ESO

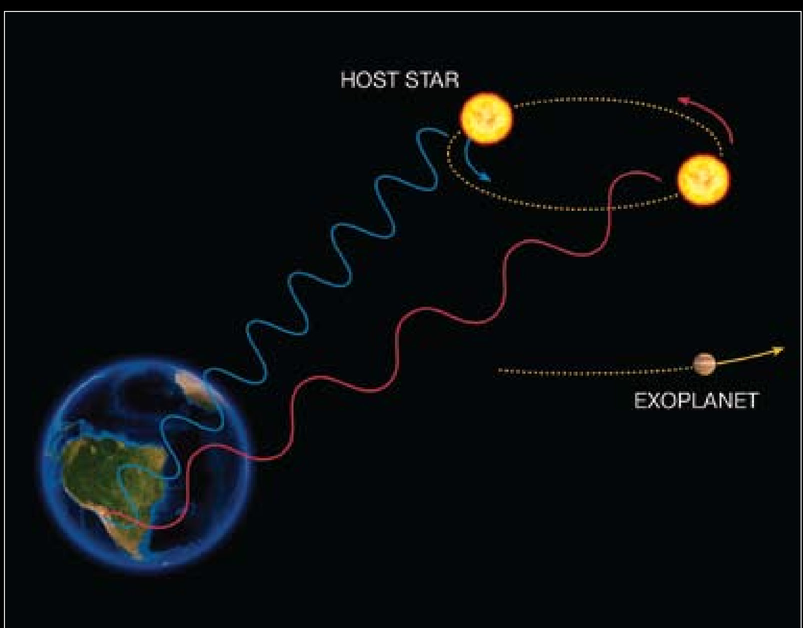
Radial velocity tracking

An astronomer can determine much information about a distant star by recording its spectrum. As the star moves in the small orbit resulting from the pull of the exoplanet, it will move towards the Earth and then away as it completes an orbit. The velocity of the star along the line of sight of an observer on Earth is its radial velocity. Changes in the radial velocity of the star cause the lines in the star's spectrum to shift towards redder wavelengths when the star is moving away from us and towards bluer wavelengths when the planet is approaching us (see image). This is the Doppler effect, and is noticeable with sound waves in everyday life, for example in the change of pitch of an ambulance siren as it drives past on the street.

The periodic changes in the star's radial velocity depend on the planet's mass and the inclination of its orbit to our line of sight. These tiny changes or "wobbles" can be measured by a distant observer. Astronomers use high precision spectrographs to study Doppler-shifted spectra, looking for small regular variations in the radial velocity of a star. As the inclination of the planetary orbit is unknown, the measurement of this regular variation gives a minimum value for the mass of the planet.

The radial velocity method has proven to be the most successful in finding new planets. At present, the most successful low-mass extrasolar planet hunter is HARPS (High Accuracy Radial Velocity for Planetary Searcher), which is mounted on the ESO 3.6-metre telescope at La Silla, Chile.

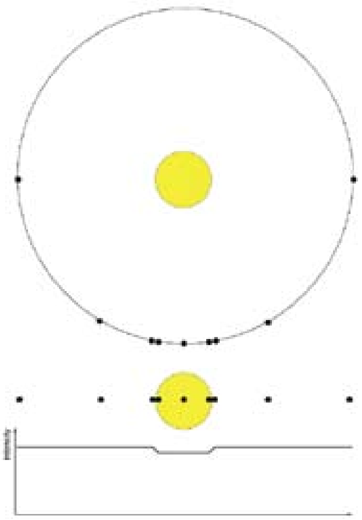
The Planetary
System around
Gliese 581
(Artist's impression)
ESO



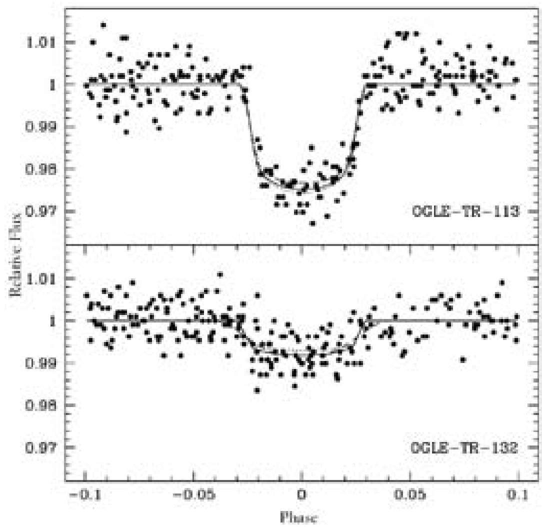
The Radial
Velocity Method
ESO

II

I



The measured drop in brightness of the star when the planet passes in front of it. ESO



Brightness Variations of Two Stars with Transiting Exoplanets | ESO

Astrometry

The astrometry method is similar to radial velocity tracking and is used to detect extrasolar planets by measuring the small regular perturbation in the position of a star due to its unseen companion. The star moves in a tiny circular orbit on the sky with a radius that depends on the mass of the planet and its distance from the star, but not on the inclination. No planet discoveries have been reported so far using this method.

Pulsar Timing

The presence of a planet orbiting a star affects the timing of the regular signals emitted by the star itself. This phenomenon can be used to detect planets around a pulsar. Pulsars emit radio waves regularly as they rotate, creating a periodically pulsed beam, like a lighthouse. If an orbiting planet perturbs the motion of the star, then the timing of the beam is also affected, and this is how the first extrasolar planets were detected.

Transits

When a planet passes between the Earth and its host star, this is known as a transit. The planet blocks some of the starlight during the transit and creates a periodic dip in the brightness of the star. This effect can be measured using photometry, which measures the amount of light coming from celestial objects.

We can learn much about the composition of a planet's atmosphere from planetary transits. As a planet passes in front of its star, light from the star will pass through the planet's atmosphere, where some of it is selectively absorbed. By comparing the "before" and "after" spectral data of the starlight, the composition of the planet's atmosphere can be deduced.

The Optical Gravitational Lensing Experiment (OGLE) located at Las Campanas, Chile, was used to find the first planet through transit photometry (called OGLE-TR-56).

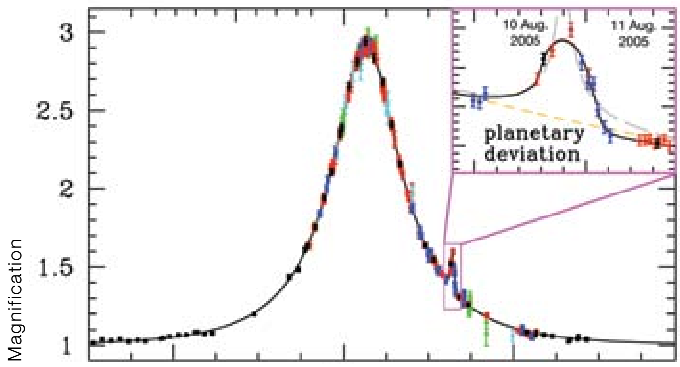
Radial velocity measurements, combined with transit photometry, make it possible to determine not only the mass of a planet, but also its radius and density.

The Crab Nebula
ESO

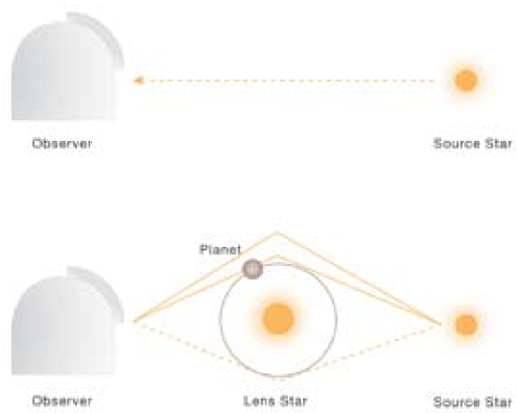
Gravitational Microlensing

The gravity of a large object will bend the light from distant objects and amplify it, acting like a magnifying lens. When light from the background object travels toward Earth, its path is bent or warped as it bypasses any large foreground object that is aligned with the background light source. As the microlensing effect works on radiation from the background source, this technique can be used to study intervening objects that emit little or no light, such as black holes, or planets around distant stars. Suppose that the aligned foreground mass to be studied is a star that is hosting a planet, then the amplified light curve from the background source will contain an additional side peak. The size and shape of the secondary peak will depend on the mass and distance of the planet from the host star (see the image).

The extrasolar planet OGLE 2003-BLG-235/MOA 2003-BLG-53 was the first planet discovered using this technique, in 2003. The disadvantage of the microlensing technique is that the effect happens only once, as it relies on a unique chance alignment of the foreground and background stars, and so measurements must be checked using other methods.



Light Curve of OGLE-2005-BLG-390 | ESO



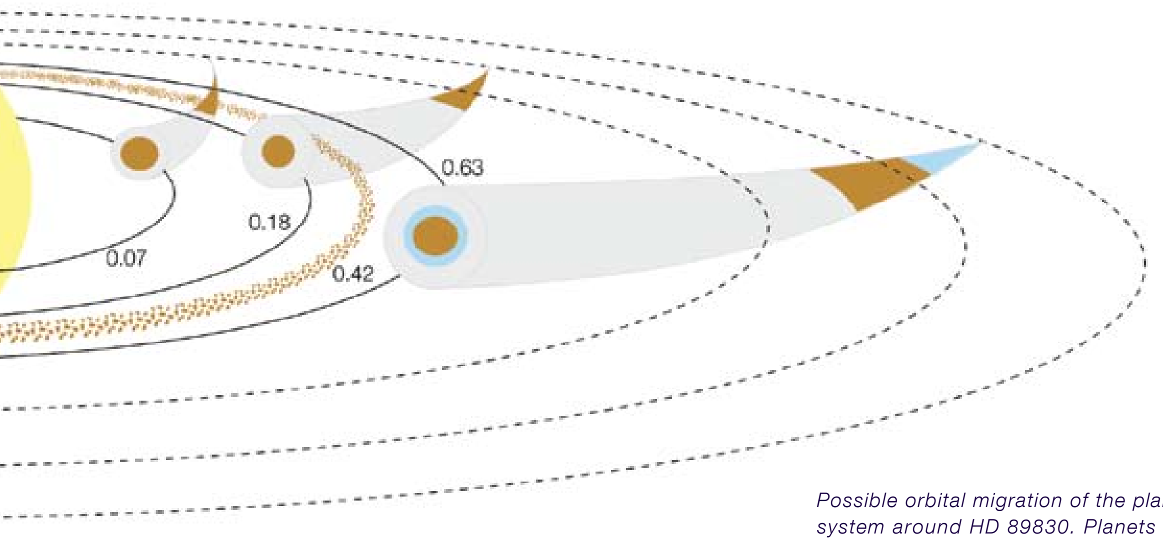
Gravitational lensing caused by the presence of a star and an exoplanet | ESO

3 What can we learn from extrasolar planets?

Extrasolar planets are fascinating because they may solve mysteries about our own Solar System. There is a wealth of data available to study different types of galaxies and stars, which have enabled astronomers to develop models and theories on star and galaxy formation and to place our own galaxy and star amongst them. The Solar System is 4.6 billion years old, but there is no way to measure directly how it formed and it was, until recently, the only planetary system that we knew of, so there was nothing to compare it with. We had no idea if it was one of many, a typical example of a planetary system or a unique one-off. Studying the formation of other young planetary systems may give us answers.

Protoplanetary discs are regions of dust and gas orbiting very young stars, where planets are formed. Current theories of planetary formation suggest that dust particles start to collapse under gravity and stick together, forming bigger and bigger grains. If young protoplanetary discs survive the threat of stellar radiation and impacts by comets and meteorites, then matter continues to clump together and eventually planetoids may form. Planetoids are celestial objects bigger than meteorites and comets, but smaller than planets. After a few million years, most of the circumstellar dust will have been swept away as planetoids accumulate mass and grow into planets.

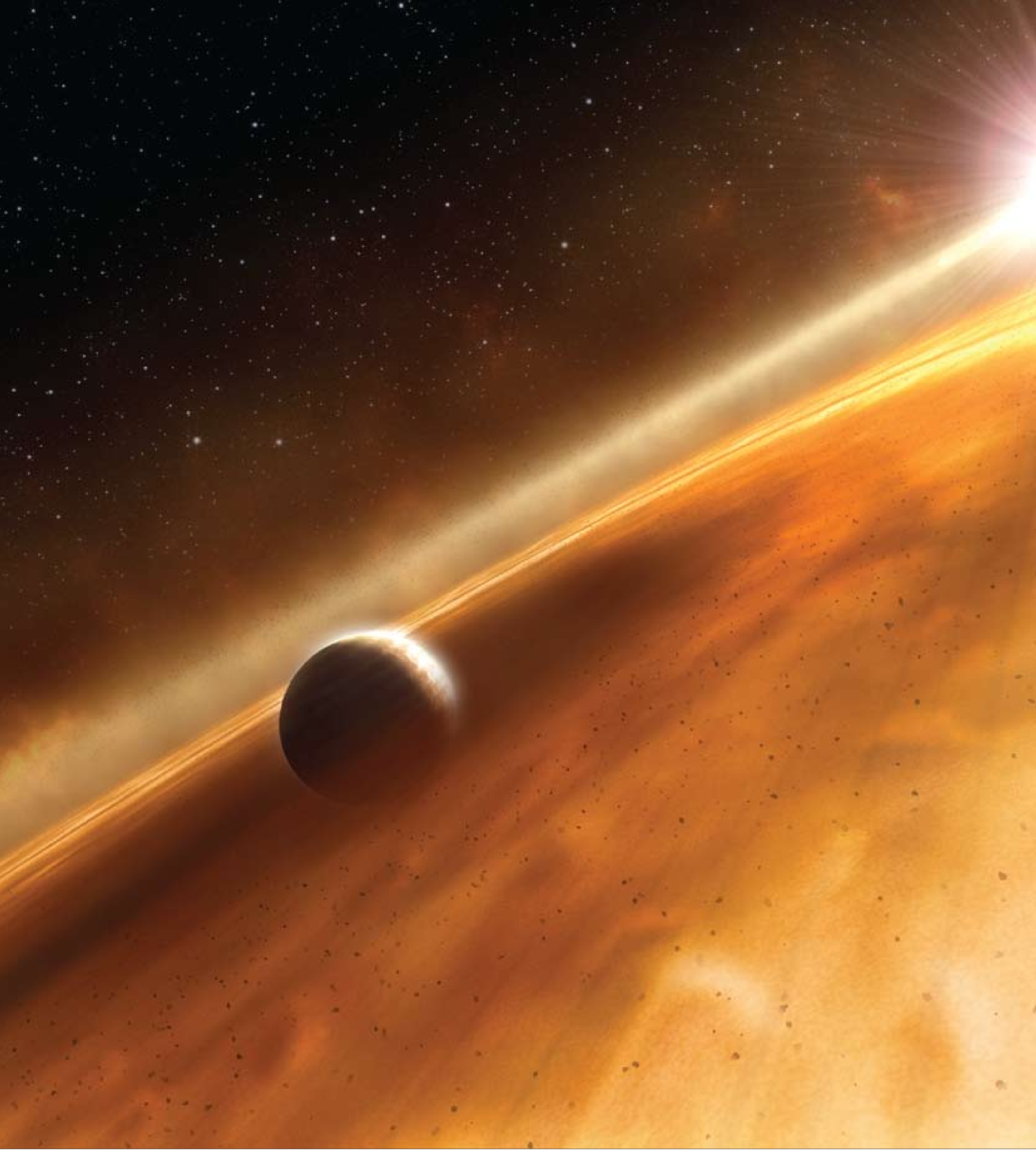
Most of the planets found so far are large, gaseous and very close to their star, unlike the situation in our own Solar System. The concept of orbital migration has been revived to explain the close proximity of some giant planets to their star: these planets may have formed undisturbed relatively far from the star and then slowly spiralled inwards over time.



Possible orbital migration of the planetary system around HD 89830. Planets may have formed far away from the star and spiralled in over time. | ESO


The central region of the Orion Nebula | ESO, M.McCaughrean et al. (AIP)

Planet-forming disc
(Artist's Impression)
ESO



Artist's concept of exoplanet orbiting Fomalhaut | ESA, NASA and L. Calçada (ESO)

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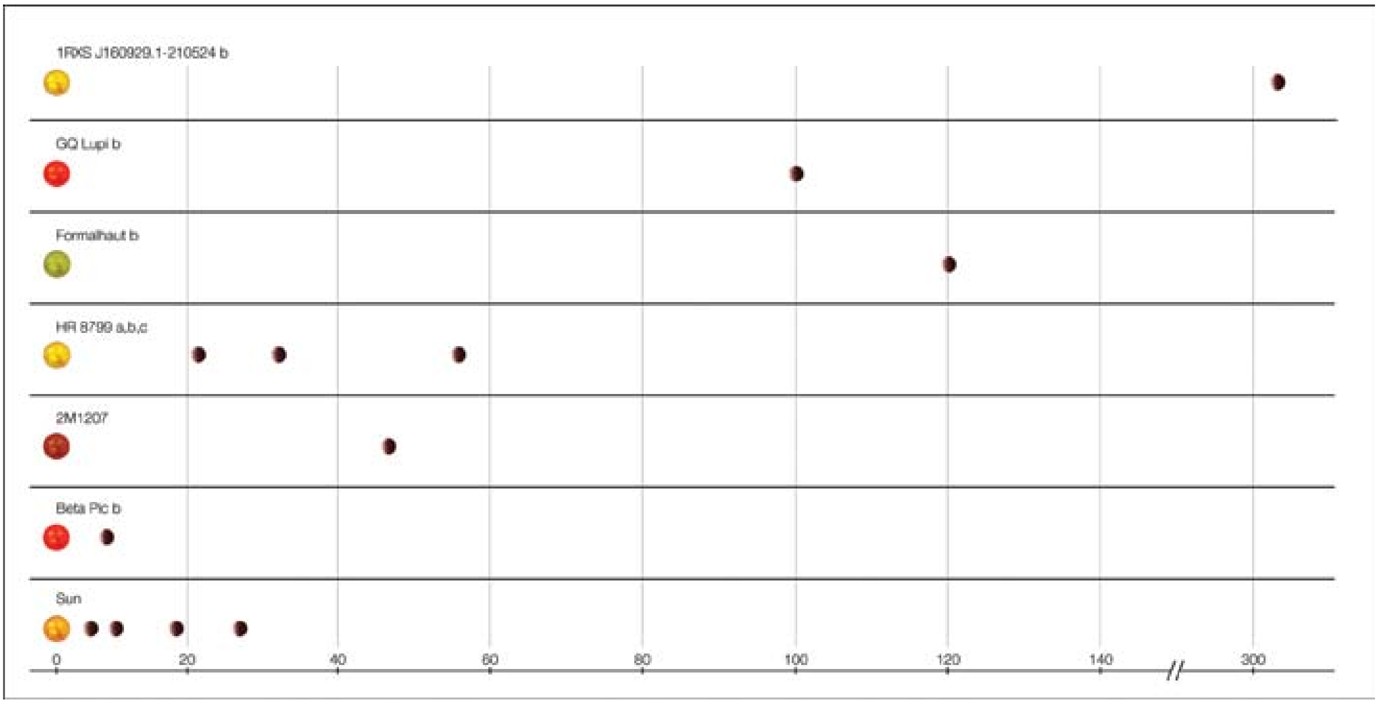
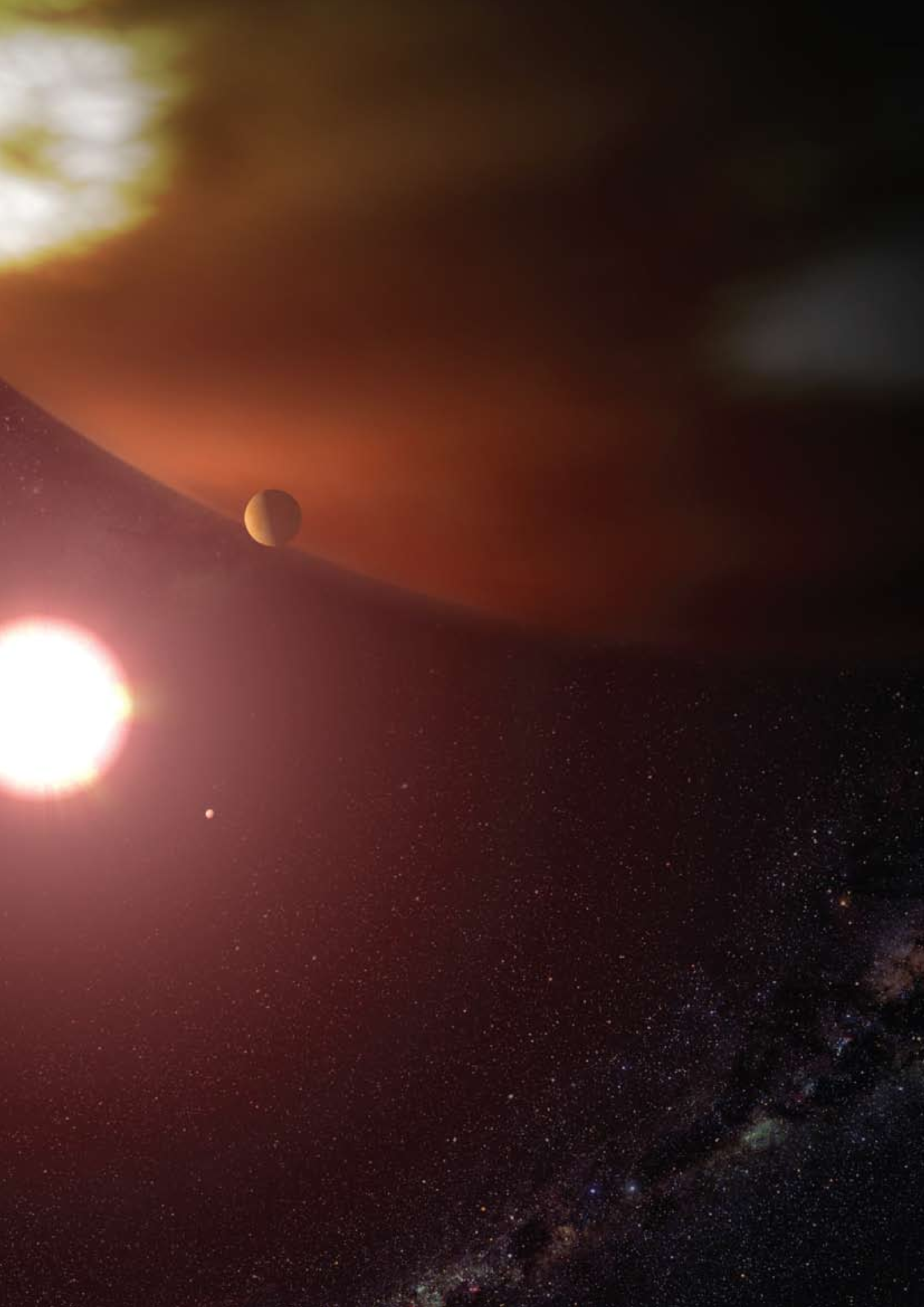
What are extrasolar planets like?

Due to the limitations in current detection methods, the majority of planets discovered so far have been rather large — Jupiter-sized or much larger. Although it is difficult to detect smaller planets, a planet less than twice the mass of the Earth has been discovered.

There are small icy extrasolar planets as well as gigantic hot planets. One of the interesting questions to answer is how the distribution of extrasolar planet type is linked to the type of parent star. It is likely that there are also extrasolar planets with rings and satellites, but these are difficult features to detect.



This diagram compares our Solar System with some of the various planetary systems detected so far (at the bottom of the image, showing the Sun along with the four outer planets, Jupiter, Saturn, Uranus and Neptune). | ESO



Life outside the Solar System

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The current focus of research into extrasolar planets is to develop the theories and understanding of planetary formation, and to understand how the Solar System developed and what its future might be. However, what makes extrasolar planets truly fascinating for most is the possibility of finding another world that harbours life.

Exobiology is concerned with the study of life outside of the Earth. The concept of "life" is subject to debate, but there is agreement in defining the features that could permit the development of carbon-based life:

- A planet should have a mass of between 1 and 10 terrestrial masses, be big enough to hold its atmosphere, but not so massive that it keeps too much hydrogen.
- A planet must be in the habitable zone, sometimes called the Goldilocks Zone, which is defined as the band around a star where water can be liquid. This means that a planet can neither be too close nor too far from its star, as water would be either gaseous or icy respectively.

Exobiology is not a focus of current extrasolar planet research projects, but is one for the future. Future spectroscopic missions — ESA's Darwin and NASA's Terrestrial Planet Finder missions — are planned for launch over the next decade and will search for oxygen, carbon dioxide and chlorophyll.

Artist's impression of an extrasolar planetary system (NASA, ESA and G. Bacon)

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Extrasolar planet research at ESO

A list of the most recent ESO achievements is given below.

- **2009:** Lightest extrasolar planet found using the most successful low-mass extrasolar planet hunter in the world, the HARPS spectrograph.
- **2008:** First planet discovered around a fast-rotating hot star, discovered by three undergraduate students and confirmed by ESO's VLT.
- **2008:** First direct image of a planet that is as close to its host star as Saturn is to the Sun.
- **2008:** Unsurpassed details revealed on the motion and makeup of planet-forming discs around Sun-like stars.
- **2008:** A trio of super-Earths are observed using ESO's HARPS instrument. Data suggests one in three Sun-like stars have such planets.
- **2007:** Discovery that extrasolar planets may pollute the atmospheres of their parent stars with planetary debris.
- **2007:** ESO develops a new imaging spectrograph so as to be able to image faint objects obscured by their bright parent stars directly. This paves the way for many thrilling new discoveries.
- **2007:** Discovery of the most Earth-like planet: located 20 light-years away, it may have water on its surface.
- **2006:** Observations show that some objects that are several times the mass of Jupiter have a disc surrounding them and may form in a similar way to stars. It thus becomes much more difficult to define precisely what a planet is.
- **2006:** Detection of three Neptune-like planets, each of a mass between ten and 20 times that of Earth, around a star that also possesses an asteroid belt. Of all known systems, this is the most similar to our own Solar System.
- **2006:** Discovery of the first terrestrial-sized extrasolar planet, five times the size of the Earth.
- **2005:** Discovery of a planet with a mass comparable to Neptune around a low-mass star, the most common type of star in our galaxy.
- **2004:** Ingredients for the formation of rocky planets discovered in the innermost regions of protoplanetary discs around three young stars. This suggests that the formation of Earth-like planets may not be unusual.
- **2004:** First direct image taken of an extrasolar planet, paving the way for more direct studies.
- **2004:** Discovery of the first possible rocky extrasolar planet, an object with 14 times the mass of the Earth.
- **2004:** Confirmation of the existence of a new class of giant planet. These planets are extremely close to their host stars, orbiting them in less than two Earth days, and are therefore very hot and "bloated".
- **2002:** The discovery of a dusty, opaque disc surrounding a young Sun-like star, in which planets are forming or will soon form. This disc is similar to the one in which astronomers think the Solar System formed.

Current ESO extrasolar planet instruments

The groundbreaking discoveries of recent years were possible thanks to the ESO instruments searching for extrasolar planets:

- HARPS (High Accuracy Radial Velocity for Planetary Searcher) on the ESO 3.6-metre telescope at La Silla for radial velocity high resolution spectroscopy. It can measure velocities with a precision greater than 1 m/s (or 3.6 km/h).
- NACO on VLT at Paranal — an active optics and near-infrared imager and spectrograph that allows the sharp imaging of objects smaller and fainter than stars, such as extrasolar planets.
- UVES on VLT — for radial velocity high resolution spectroscopy in the UV and visible.
- EMMI on NTT at La Silla — spectrograph operating at visible wavelengths.
- FLAMES (Fibre Large Array Multi Element Spectrograph), on ESO's VLT at Paranal — for multi-fibre resolution spectroscopy.
- 1.2-metre Swiss Telescope at La Silla — high resolution spectroscopy.
- 1.54-metre Danish Telescope at La Silla — long-term monitoring.
- AMBER studies of circumstellar environments and protoplanetary discs, important for planet formation studies.
- VISIR studies of circumstellar environments and protoplanetary discs, important for planet formation studies.
- ISAAC
- MIDI at ESO's VLTI

Extrasolar planet research in the future at ESO

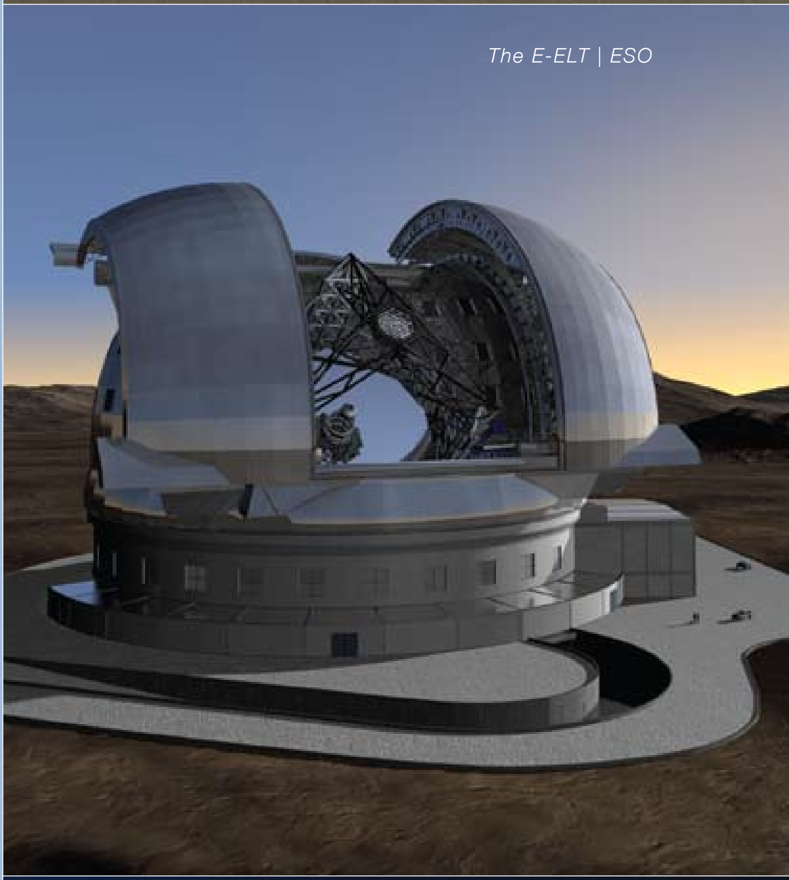
The PRIMA instrument of the ESO Very Large Telescope Interferometer (VLTI), which recently saw "first light" at its new home atop Cerro Paranal in Chile, will boost the capabilities of the VLTI to see sources much fainter than any previous interferometers, and enable astrometric precision unmatched by any other existing astronomical facility. PRIMA will therefore be a unique tool for the detection of exoplanets.

The second-generation instrument SPHERE for ESO's Very Large Telescope is dedicated to the discovery and study of new extra-solar giant planets orbiting nearby stars by direct imaging, in particular of planets more massive than Jupiter at various stages of their evolution, in the key separation regime 1 to 100 AU. SPHERE should have first light in 2010.

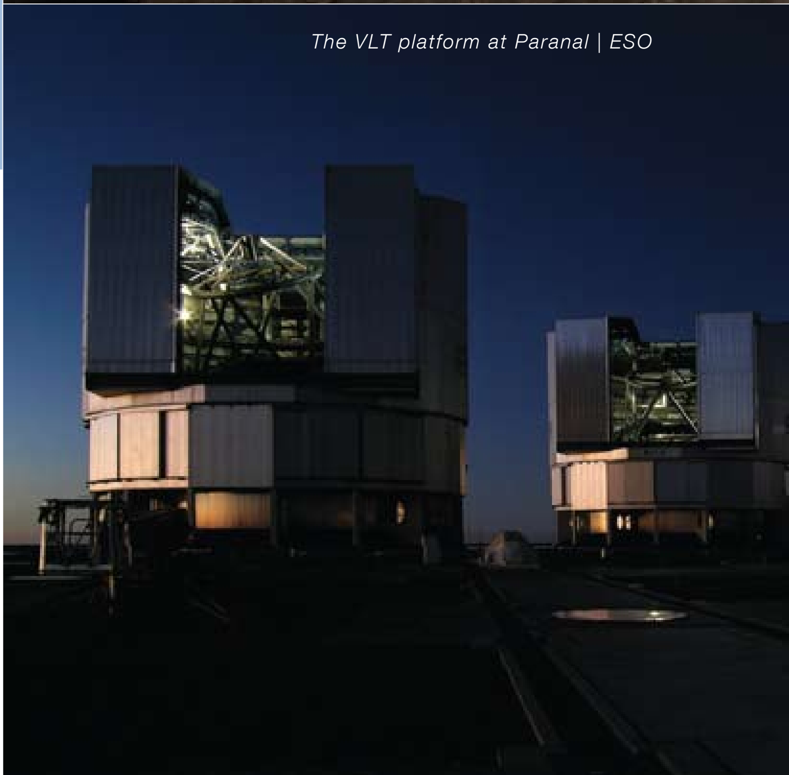
Moreover, two future ground-based telescopes will be used to search for extrasolar planets:

- E-ELT (European Extremely Large Telescope) — expected to be able to image extrasolar planets directly, revealing their composition, and to detect via the radial velocity method Earth-mass planets.
- ALMA (Atacama Large Millimeter/submillimeter Array) — for accurate astrometry measurements, possibly even for direct detection. Detailed mapping of protoplanetary discs, which is important for understanding planet formation.

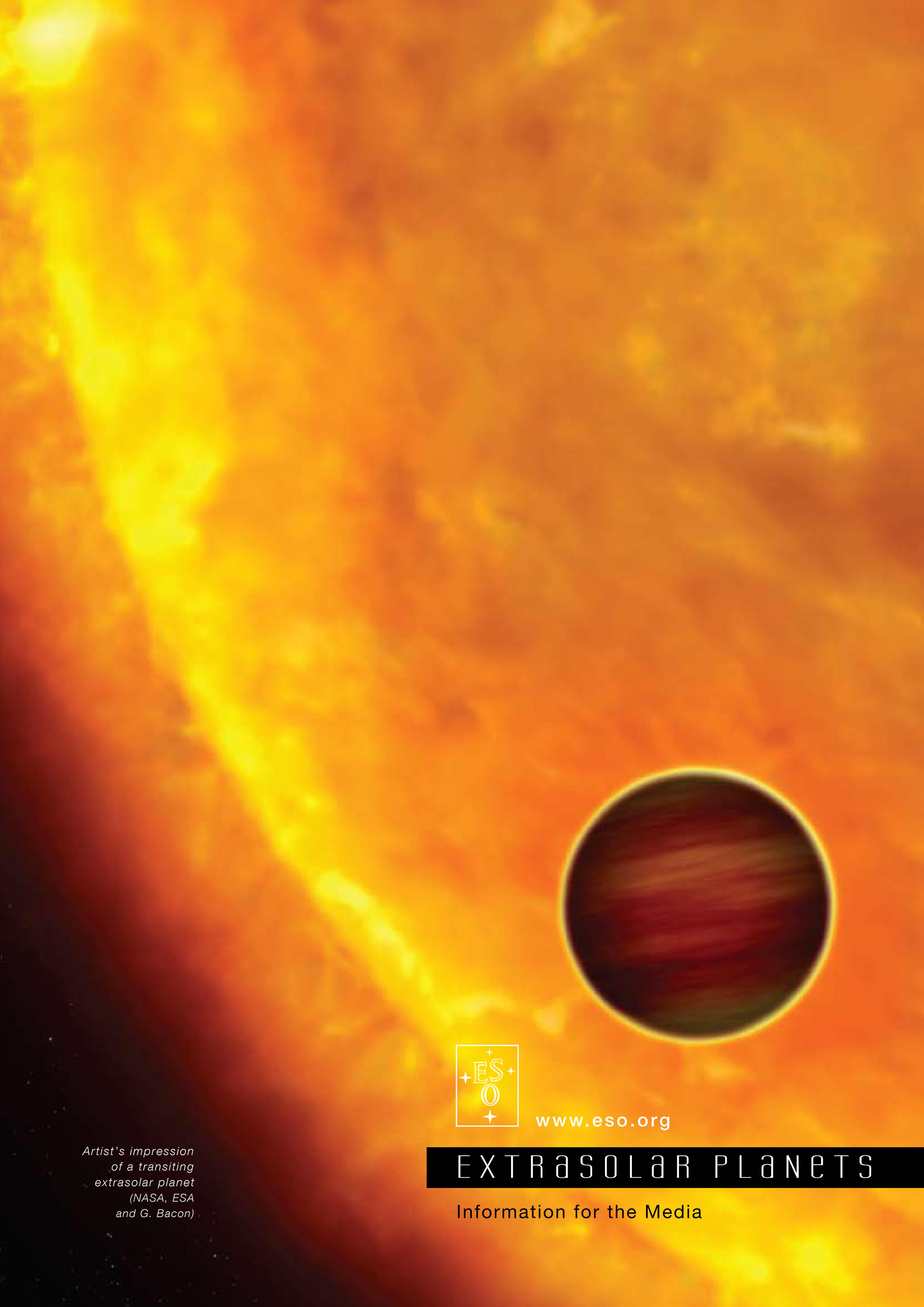
The ALMA array | ESO



The E-ELT | ESO



The VLT platform at Paranal | ESO



Artist's impression of a transiting extrasolar planet (NASA, ESA and G. Bacon)

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