Exoplanets Booklet

Exoplanets and how to find them

What are exoplanets?

The Copernican revolution made us aware that Earth is a planet orbiting the sun. Copernicus's studies opened up the possibility of the existence of planets orbiting other stars than the sun: the exoplanets.
The first exoplanets were detected in the 1990s, today the count of confirmed exoplanets is almost four thousand and it is raising.

> Exoplanets: a planet which exists outside Earth's solar system.

The detection of exoplanets has crucial implications for our understanding of our role in the universe. In fact, it made us conscious about three facts:

- planets are common in the universe;
- life elsewhere might exist;
- comparing Earth to many other planets allows us to learn how planets form, and by inference, how our planet has formed.

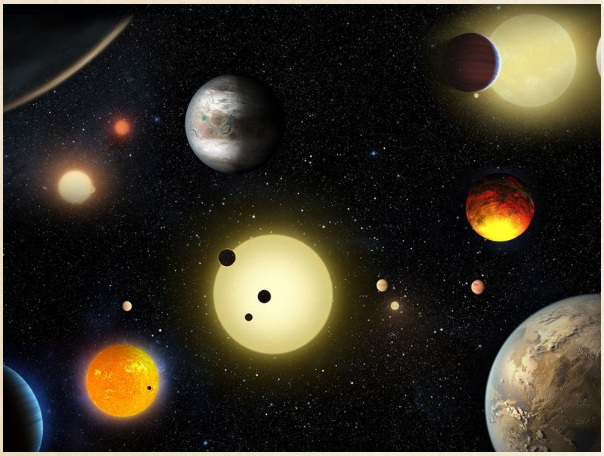

Figure 1: An artist's impression of exoplanets. (NASA/W. Stenzel)

Detecting exoplanets

Even more fun!

How do we look for them?

Detecting exoplanets poses an immense technological challenge for two reasons:

– planets are really tiny compared to distances between stars;
– stars are a billion times brighter than the light reflected by their planets; the starlight hides the "planetary light".

Warning!
Exoplanets are quite difficult to observe with telescopes. They are tiny and hidden by the bright stars they orbit.

To understand how scientists overcome the above challenges it is worth recalling that there are two ways of getting information about a distance object, for example a planet:

– *directly*, by obtaining spectra or images of the planet;
– *indirectly*, by inferring the planet's existence without seeing it.

To date, the indirect approach has contributed the most in building our knowledge about exoplanets. Nearly all exoplanets detected so far, have been discovered indirectly rather than through direct observation. In fact, we still need significant advances in technology to get a high-resolution spectra or image of an exoplanet.

Two are the main indirect techniques to find and study exoplanets:

– to look for wobbly stars: the **astrometric** and **Doppler methods**. A star with planets does not orbit perfectly around its center. The "wobble" is a consequence of the presence of orbiting planets;
– to observe changes to a star's brightness caused when its planets pass in front of the star: the **transit method**.

The earliest detections of exoplanets were achieved using the first method. However, the second method, named the transit method, has provided to date the largest amount of discoveries.

Important facts

Nearly all exoplanets detected so far, have been discovered indirectly rather than through direct observation.

The transit method

This method of indirectly detecting exoplanets consists of observing slight changes in a star's brightness. These changes are provoked by orbiting planets.

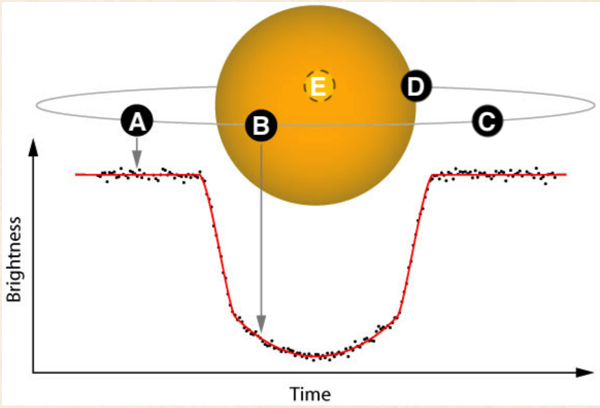

Figure 2: Cartoon showing a planet-star system before transit (A), during transit (B), after transit (C), before eclipse (D) and during eclipse (E). (ESO)

Astronomers observe a **transit** when a planet moves across the face of the star (Fig.2). Prior to the transit, the star has its full visible-light brightness as viewed from Earth (Fig.2 A).

When a planet happens to transit in front of a star, it attenuates the star's brightness (Fig.2 B), so that the star dims as seen from Earth. If we would have to plot the light curve of the star as function of time we would notice, during the transit, a dip in the system's brightness. The larger the planet crossing the face of the star, the more dimming.

Some transiting planets are characterized by a measurable **eclipse** when they pass behind the star (Fig.2 E).

Prior to the eclipse, the system's brightness receives the contributions of both stars and planets (Fig.3, panel 2 C,D). During the eclipse, the planets contribution is blocked by the star (Fig.3, panel 2 E).
Eclipses observations are preferably carried out in the infrared. This is because the planets contribute more to the system's infrared brightness than to the system's visible-light brightness.

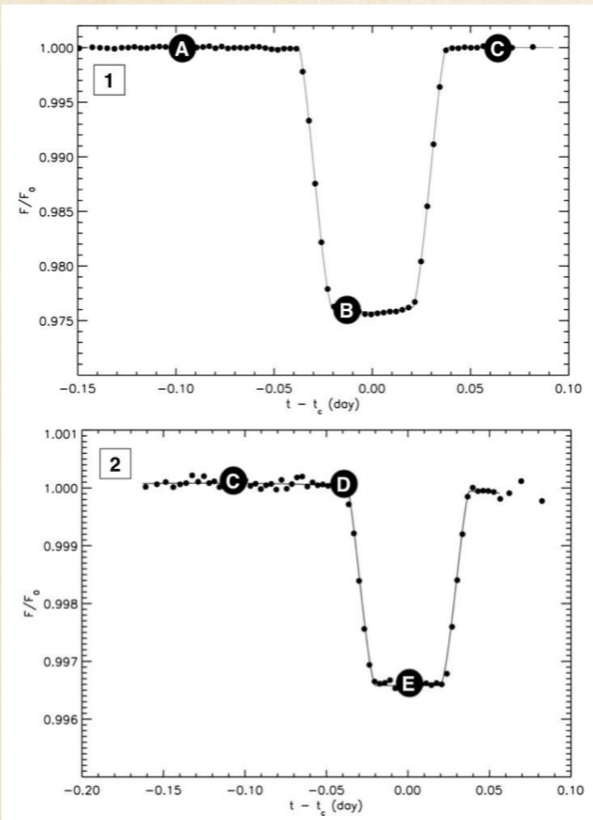

Figure 3: Transits and eclipses of the planet orbiting the star *HD 189733 b*. (Agol et al. 2010)

To detect exoplanets using the transit method it is necessary to regularly monitor a star system's brightness over a large period of time. It is important to keep in mind that generally stars show intrinsic variations in brightness and these are not necessarily attributable to the presence of an orbiting planet.

Important facts

At least three repeated transits have to be observed before astronomers can infer the detection of a planet.

In order to claim the detection of a planet, it is thus necessary to observe repeatedly, over a regular period, the same dips in brightness. This means that the same planet is crossing the face of the star at the same time during each of its orbits. The period of the repeated transits is called the **orbital period** of the planet.

A little bit of... history

The first detection

51 Pegasi b, also known as "Dimidium", was the first exoplanet ever discovered, back in 1995 (Fig.4). *51 Pegasi b* orbits a star like our sun called *51 Pegasi*.
The detection of *51 Pegasi b* was groundbreaking: it confirmed that planets could exist outside our solar system.

Figure 4: *51 Pegasi b*, the first exoplanet ever discovered. (NASA/JPL)

51 Pegasi b is about half the size of Jupiter and it has a orbital period of only four days. It was discovered using the wobble method (not the transit!) by the European team led by Michel Mayor and Didier Queloz (Fig.5).

IMPORTANT FACTS
51 Pegasi b was the first exoplanet ever discovered orbiting a star like our sun. The detection dates back to 1995.

After the discovery of *51 Pegasi b*, the exoplanet hunt race was on. Less than one year later the discovery of other two exoplanets was announced: *70 Virginis* and *47 Ursae Majoris*.
By using the wobble method, astronomers were able to detect around 100 exoplanets in the decade following the discovery of *51 Pegasi b*. Then a new planet-hunting method, the transit method, stole the show.

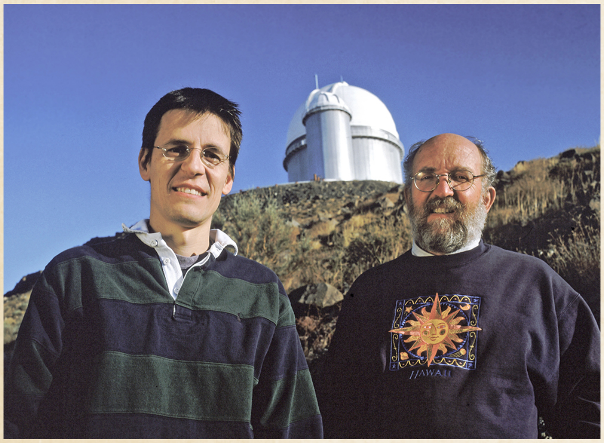

Figure 5: Didier Queloz and Michel Mayor, the pair who discovered *51 Pegasi b*. (L. Weinstein)

IMPORTANT FACTS
To detect a planet with an Earth-like orbit astronomers have to monitor a star's system for at least about three years.

THE KEPLER SPACE TELESCOPE

THE EXOPLANETS HUNTER N.1

NASA's **Kepler Space Telescope** was launched in 2009, opening a new era of exoplanet hunting (Fig.6). It sought for planetary transits until 2013. Throughout these four years, the Kepler telescope monitored up to 150000 stars. It measured their brightness every 30 minutes to catch tiny dips caused by planets crossing in front of them.

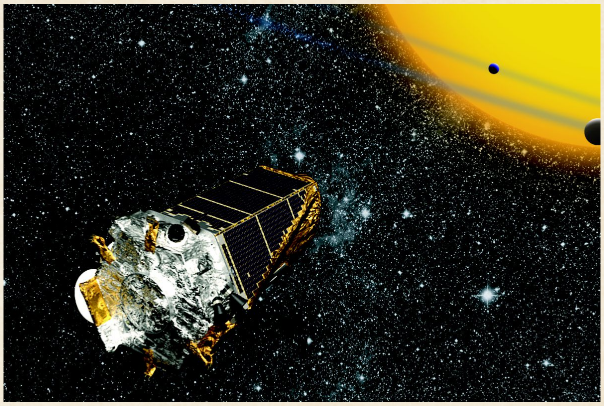

Figure 6: NASA's Kepler Space Telescope. (NASA/JPL-Caltech)

The result: around 2,500 confirmed exoplanets were discovered by Kepler so far, and thousands of planetary candidates have been observed but not yet confirmed. Nowadays, Kepler's four years of collecting data are still revealing new exoplanets.

IMPORTANT FACTS
NASA's Kepler Space Telescope opened a new era of exoplanet hunting. Using the transit method, it monitored up to 150,000 stars every 30 minutes for four years.

Some of the exoplanets discovered by Kepler are rocky planets like Earth. They orbit the host star at a special distance. Astronomers refer to this "sweet spot" as the **habitable zone**, where life could emerge (or has emerged already!).

HOW MANY SOLAR SYSTEMS ARE IN OUR GALAXY?

Our solar system is a planetary system: a star with planets orbiting around it. Our Sun is only one of 200 billion stars in our galaxy. Like our Sun, those 200 billion stars might have planets orbiting around them (Fig.8).
As 2019, almost 4,000 exoplanets have been detected in our Galaxy.
The detected exoplanets show a variety of sizes, masses and densities.
For example, planet *HD 40307g* is a Super Earth, it has a mass eight times bigger than Earth. This means that the gravitational force is much stronger on *HD 40307g* than on Earth. On planet *HD 40307g* you would weight the double!
Another fascinating planet, *Kepler-16b*, orbits two stars. On *Kepler-16b* you would be able to experience the sunset of two setting stars (Fig.7).

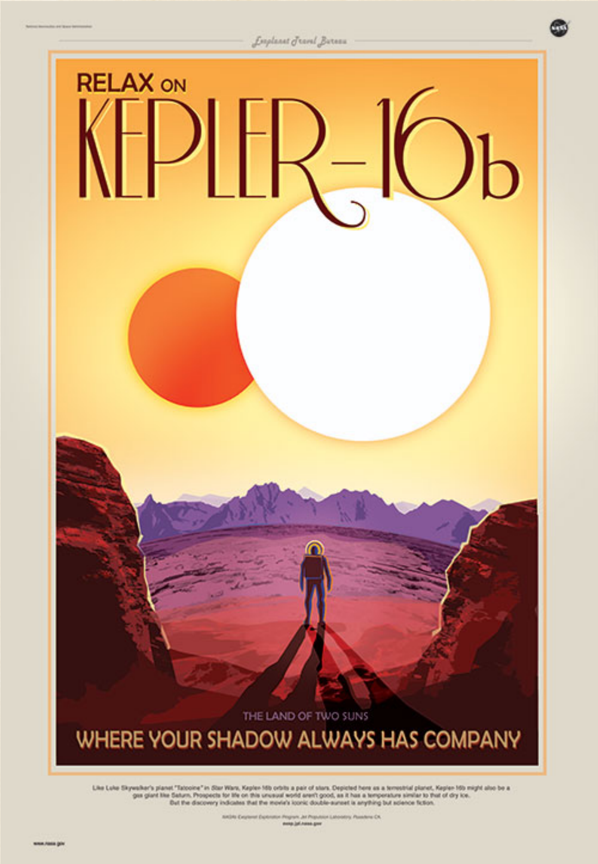

Figure 7: Artistic illustration of how it would look like to watch the sunset on planet *Kepler-16b*.(NASA/JPL-Caltech)

EXOPLANETS PROPERTIES

Despite the difficulties in detecting exoplanets, it is possible to learn a surprising amount of information about them. The scheme below lists some of the properties of exoplanets.

Planetary Properties and Methods
`period`: astrometric, Doppler, transit
`distance`: astrometric, Doppler, transit
`mass`: astrometric, Doppler
`size (radius)`: transit
`density`: transit + Doppler
`temperature`: transit
`atmospheric composition`: transit

Is our solar system common?

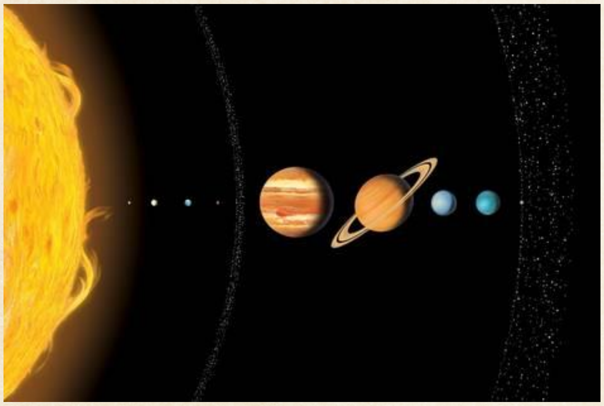

Figure 8: Our solar system. (NASA)

The Kepler mission provided information about so many exoplanets that it made possible for astronomers to use statistics to infer whether our solar system is common or not in our galaxy. So far we have learned that:

- many exoplanets orbit unexpectedly closer to their star and with almost circular orbits;
- smaller planets seem to be more common than larger planets and thus Earth-like planets may also be common;
- at least 70% of all stars host at least one planet.

The Kepler data suggests that smaller planets are more common than larger ones and, by inference, that Earth-like planets may be common. However, it is important to state that Kepler was mainly monitoring Earth-like planets characterized by Earth-like orbital period and distances.

To determine the nature of an exoplanet which means understanding whether it is terrestrial or jovian it is necessary to measure both its mass and the size to calculate its density. The outcomes of this calculations provide an interesting results: the densities of exoplanets vary over a larger range with respect to the solar system's density. Some exoplanets show densities comparable to the density of iron, others have densities as low as polystyrene.

Do exoplanets fall into terrestrial or jovian types or do we find different types of planets? Unfortunately we are not able to answer this question because we do not have yet the capacity of directly obtain highly detailed spectra determining the chemical composition of exoplanets.
As of January 2019, we do not have discovered yet a planetary system which looks like ours: does this mean that our solar system is rare or we do not have obtained enough data to prove that our solar system is common? If there are plenty of planetary systems like ours, it is reasonable to think that Earth-analogs and also life and civilization are diffuse. On the contrary, if our solar system is unique or rare than Earth might be the only inhabited planet in our galaxy or in the entire universe.

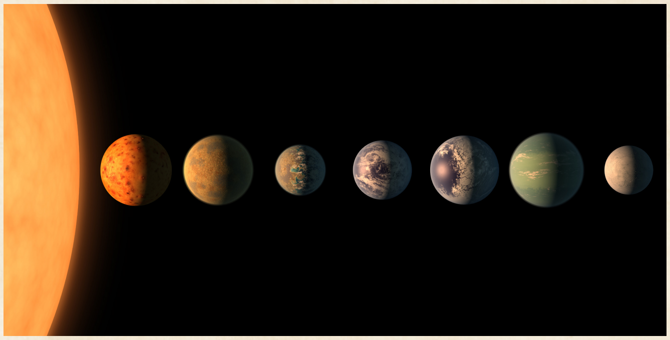

Figure 9: The planetary system TRAPPIST-1. (NASA/JPL-Caltech)

A planetary system similar to ours has not been discovered yet but, a very interesting system composed of seven Earth-size planets has been detected.
The planetary system is named after the telescope which first discovered the planets: **TRAPPIST- 1** (Fig.9). TRAPPIST-1 is located 40 light years away and it has been observed with several facilities, both ground-based and space-based telescopes (e.g. TRAPPIST, Hubble Space Telescope, Spitzer Space Telescope, etc.).
Among all the seven planets, three of them are located in the habitable zone and thus are likely to hold liquid water. This groundbreaking discovery was announced on February 2017.
The TRAPPIST-1 planets are really close one another: if you could stand on the surface of one of the TRAPPIST-1 planets, you might be able to see some of the neighboring planets hovering above you.

Figure 10: Illustration of planetary system TRAPPIST-1. (NASA/JPL-Caltech)

TESS: Transiting Exoplanet Survey Satellite

On April 2018, **TESS**, the Transiting Exoplanet Survey Satellite was launched. TESS is the "new Kepler" in the search for exoplanets and it will survey 200,000 of the brightest stars near the sun. The main objective of the mission is finding transiting exoplanets, which means detecting exoplanets periodically blocking the light from their host stars.

Figure 11: Conceptual image of the TESS mission. (MIT)

Astronomers expect the TESS mission to catalog thousands of exoplanets and significantly increase the list of known exoplanets. Of these, around 300 are supposed to be Earth-sized and super-Earth-sized exoplanets, which have masses not bigger than twice the Earth-size. Both these types of planets could bring information about life elsewhere in the universe.
TESS is expected to find the most promising exoplanets hosted by our nearest and brightest stars, providing astronomers with a rich set of new targets. These will be analyzed to get a more and more precise idea about planets in the universe and life outside the solar system.

Glossary

astronomical unit: the average distance of Earth from the Sun.

binary star system: a system composed of two stars.

center of mass: the point around which two orbiting objects orbit.

Doppler technique: the detection of exoplanets through the motion of a star toward and away from the observer caused by gravitational tugs from the planet.

eclipse: event during which the planet passed behind its star as viewed from Earth.

habitable zone: the region around a star in which planets could potentially host liquid water.

hot Jupiter: a class of planet that has size similar to Jupiter but orbits very close to its star.

jovian planets: Giant gaseous planets similar in composition to Jupiter.

transit: an event in which a planet passes in front of a star as seen from the Earth.

visible light: the light our eyes can see ranging from 400 to 700 nm in wavelength.

wavelength: the distance between adjacent peaks of a wave.

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