Planets and exoplanets

Rosa M. Ros, Hans Deeg
International Astronomical Union, Technical University of Catalonia (Spain),
Instituto de Astrofísica de Canarias and University of La Laguna (Spain)

Summary

This workshop provides a series of activities to compare the many observed properties (such as size, distances, orbital speeds and escape velocities) of the planets in our Solar System. Each section provides context to various planetary data tables by providing demonstrations or calculations to contrast the properties of the planets, giving the students a concrete sense for what the data mean.

At present, several methods are used to find exoplanets, more or less indirectly. It has been possible to detect nearly 4000 planets, and about 500 systems with multiple planets.

Objetives

- Understand what the numerical values in the Solar Sytem summary data table mean.

- Understand the main characteristics of extrasolar planetary systems by comparing their properties to the orbital system of Jupiter and its Galilean satellites.

The Solar System

By creating scale models of the Solar System, the students will compare the different planetary parameters. To perform these activities, we will use the data in Table 1.

Planets	**Diameter (km)**	**Distance to Sun (km)**
Sun	1 392 000	
Mercury	4 878	$57.9\ 10^6$
Venus	12 180	$108.3\ 10^6$
Earth	12 756	$149.7\ 10^6$
Marte	6 760	$228.1\ 10^6$
Jupiter	142 800	$778.7\ 10^6$
Saturn	120 000	$1\ 430.1\ 10^6$
Uranus	50 000	$2\ 876.5\ 10^6$
Neptune	49 000	$4\ 506.6\ 10^6$

Table 1: Data of the Solar System bodies

In all cases, the main goal of the model is to make the data understandable. Millions of kilometers are not distances that are easily grasped. However, if translated to scaled distances and sizes, the students usually find them easier to comprehend.

Models of the Solar System

Activity 1: Models of diameters

Using a large piece (or multiple pieces if necessary) of yellow paper cut a circle representing the Sun. The Sun is scaled to be 139 cm in diameter such that 1 cm is 10 000 km. Cut the different planets out of plain cardboard or construction paper and draw their morphological characteristics. By placing the planets near the solar disk, students can grasp the different planetary scales.

With a scale of 1 cm per 10 000 km, use the following planetary diameters: Sun 139 cm, Mercury 0.5 cm, Venus 1.2 cm, Earth 1.3 cm, Mars 0.7 cm, Jupiter 14.3 cm, Saturn 12.0 cm, Uranus 5.0 cm and Neptune 4.9 cm.

Suggestion: It is also possible to complete the previous model by painting the planets on a shirt, keeping the scale of the planets but only painting a fraction of the Sun.

Fig. 1 and 2: Examples of shirts providing Solar and planetary diameter scale comparisons.

Activity 2: Model of distances

By comparing the distances between the planets and the Sun we can produce another model that is easy to set up in any school hallway. First, simply cut strips of cardboard 10cm wide, linking them up to obtain a long strip of several meters (figure 3). Then, place the cutouts of the planets on it at their correct distances. Remind the students that the distance between the planets is not to scale with diameters. At the suggested scale, the planets would be one thousand times smaller as here we are using 1 cm per 10 000 000 km, while in the first activity above we used 1 cm per 10 000 km. If using a scale of 1cm per 10 million km the scaled distances are: Mercury 6cm, Venus 11cm, the Earth 15cm, Mars 23cm, Jupiter 78cm, Saturn 143cm, Uranus 288cm and Neptune 450cm.

Fig. 3: Model of distances.

Suggestion: A fun variation of this model is to use each sheet of a toilet paper roll for scale. For example, you can take as scale a portion of paper for every 20 million km.

Activity 3: Model of diameters and distances

The next challenge is to combine the two above activities and make a model representing the bodies to scale, as well as the corresponding distances between them. It is not actually that easy to define a scale that allows us to represent the planets with objects that are not too small and still have distances that are not overly large, in which case the sizes and distances are not easily assimilated, and the model is not very useful for students. As a suggestion, it may be a good idea to use the schoolyard to make the model and use balls for the planets as balls of varying diameters are available as appropriate.

Fig. 4: The Sun and the planets of the model of diameters and distances.

As an example, we provide a possible solutioAt one end of the schoolyard we put a basketball about 25 cm in diameter that represents the Sun. Mercury will be the head of a needle (1 mm in diameter) located 10 m from the Sun. The head of a slightly larger needle (2 mm in diameter) will represent Venus at 19 m from the Sun, while Earth will be the head of another needle similar to the previous one (2 mm) at 27 m from the Sun. Mars is a slightly smaller needle head (1mm), located 41 m from the Sun. Usually, the schoolyard ends here, if not sooner. We will have to put the following planets in other places outside the schoolyard, but at landmarks near the school, so that the students are familiar with the distances. A ping-pong ball (2.5 cm diameter) corresponds to Jupiter at 140 m from the Sun. Another ping-pong ball (2 cm in diameter) will be Saturn at 250 m from the Sun, a glass marble (1 cm in diameter) will represent Uranus at 500 m from the Sun, and a final marble (1 cm), located at 800 m, will represent Neptune.

It should be emphasized that this planetary system does not fit into any school. However, if we had reduced the distances, the planets would be smaller than the head of a needle and would be almost impossible to visualize. As a final task, you can calculate what scale has been used to develop this model.

Activity 4: Model on a city map

The idea is simple - using a map of the city to locate the positions of the different planets, assuming the Sun is located at the entrance to the school. As an example, we present the map of Barcelona with different objects (specifically fruits and vegetables) that would be located on the different streets, so you can better imagine their size. As an exercise, we suggest that you do the same activity with your own city.

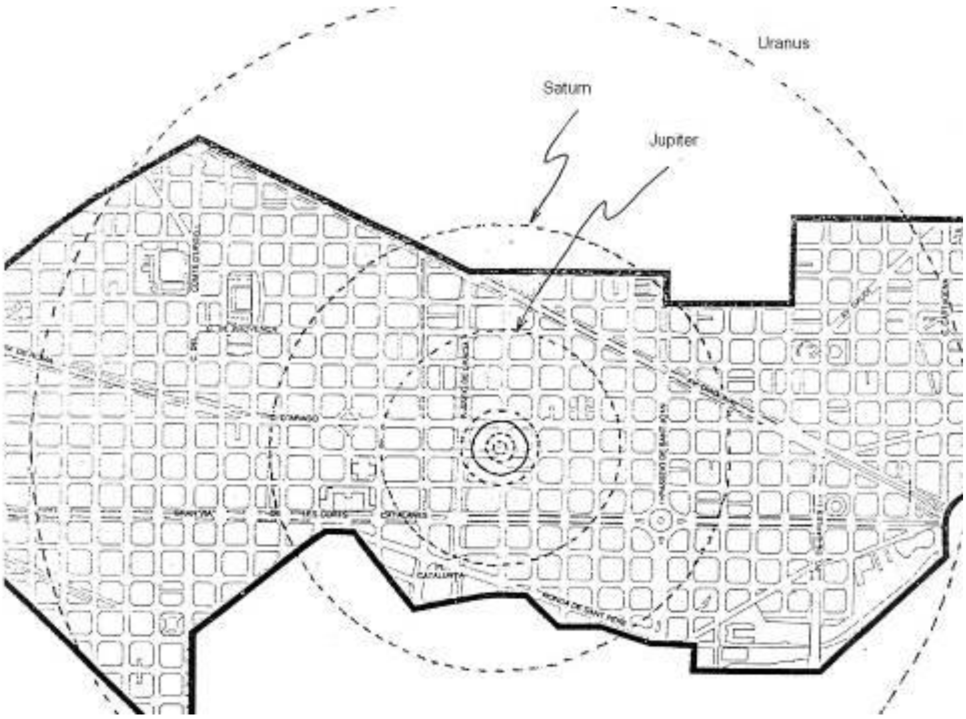


Fig. 5: Map of the “Ensanche de Barcelona” with some planets.

Using the map shown here, Mercury would be a grain of caviar, Venus and the Earth a couple of peas, Mars a peppercorn, Jupiter an orange, Saturn a tangerine and Uranus and Neptune a pair of walnuts. For the Sun, since there is no vegetable large enough, students should imagine a sphere roughly the size of a dishwasher. The instructor can do the same activity using their own city.

Fig. 6a and 6b: Snapshots of the city of Metz.

In the city of Metz (France) there is a solar system spread out on its streets and squares, with corresponding planets accompanied by information panels for those walking by.

Activity 5: Models of light distances

In astronomy it is common to use the light year as a unit of measurement, which can often be confused as a measurement of time. This concept can be illustrated using a model of the Solar System. Since the speed of light is c = 300,000 km/s., the distance that corresponds to 1 second is 300,000 km. For example, to travel from the Moon to the Earth, which are separated by a distance of 384,000 km, it takes light 384,000/300,000 = 1.3 seconds.

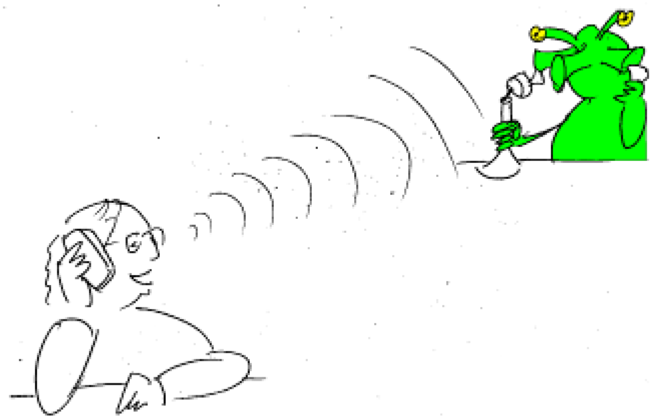


Fig. 7: Another example

Using these units, we will instruct the students to calculate the time required for sunlight to reach each of the planets of the Solar System. (For the instructor, here are the times required: the time it takes sunlight to reach Mercury is 3.3 minutes, to Venus it takes 6.0 minutes, to Earth 8.3 minutes, to Mars 12.7 minutes, to Jupiter 43.2 minutes, to Saturn 1.32 hours, to

Uranus 2.66 hours and to Neptune, 4.16 hours. You may want to ask the students to imagine what a video conference between the Sun and any of the planets would be like.

We introduce here also the distance to the nearest star because it is very useful to visualize the enormous distances to other stars, which is the reason why it is so difficult to detect extrasolar planets. The closest to us is Alpha Cetauri at a disctance of 4.37 light years or 4.13 10^{13} km. You may ask the students to calculate the distance to this star in any of the planet system models that were previously mentioned. In the "school yard model", with a scale 1 cm per 56000 km, the star would be at a distance of 7 375 km!

Activity 6: Model of the solar disk from each planet

From a planet, for example the Earth, the Sun subtends an angle α (figure 8). For very small values of α, we take tan $\alpha \approx \alpha$ (in radians)

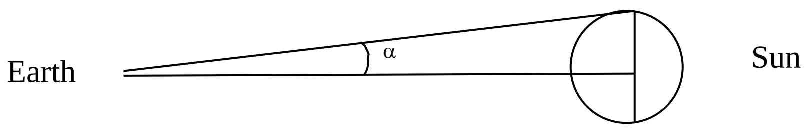


Fig. 8: From the Earth, the Sun subtends an angle α.

Knowing that the solar diameter is 1.4 $x10^6$ km, i.e. a radius of $0.7x10^6$ km, and that the Earth-Sun distance is $150x10^6$ km, we deduce:

$$\alpha \approx tg\alpha = \frac{0{,}7 \cdot 10^6}{150 \cdot 10^6} = 0{,}0045 \; radians$$

And in degrees:

$$\frac{0{,}0045 \cdot 180}{\pi} = 0{,}255^{\circ}$$

That is, from the Earth, the Sun has a size of 2 x 0.255 ≈ 0.51°, i.e., about half a degree. Repeating the same process for each planet, we get the Sun-sizes in Table 2 and we can represent the Sun's relative sizes (figure 9).

Planets	**2tan α**	**2α (º)**	**2α (º) aprox.**
Mercury	0.024	1.383	1.4
Venus	0.0129	0.743	0.7
Mars	0.006	0.352	0.4
Jupiter	0.0018	0.1031	0.1
Saturn	0.000979	0.057	0.06
Uranus	0.00048	0.02786	0.03
Neptune	0.0003	0.0178	0.02

Table 2: Sun-sizes from the different planets.

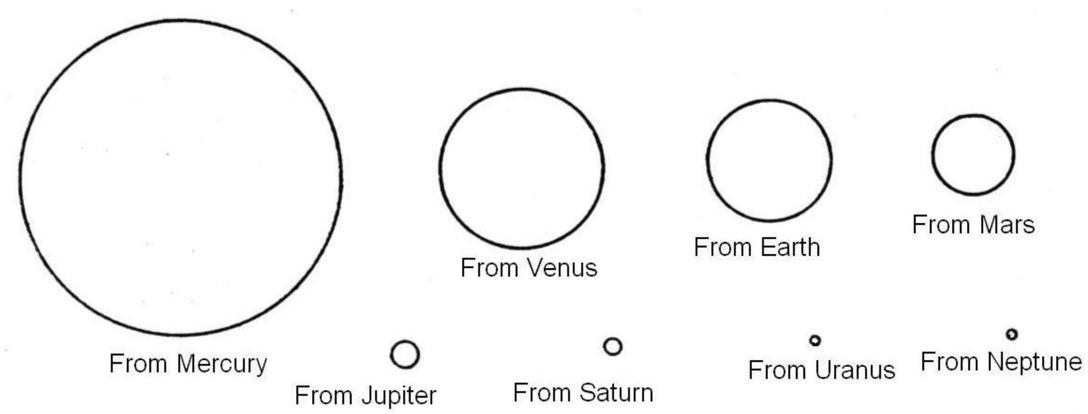


Fig. 9: The Sun seen from each planet: Mercury, Venus, The Earth, Mars, Jupiter, Saturn, Uranus and Neptune.

Activity 7: Model of densities

The objective of this model is to look for samples of materials that are easily manipulated and have a density similar to each of the solar system bodies, in order to be able to "feel it in our hands."

	Density (g/cm^3)
Sun	1.41
Mercury	5.41
Venus	5.25
Earth	5.52
Moon	3.33
Mars	3.9
Jupiter	1.33
Saturn	0.71
Uranus	1.3
Neptune	1.7

Table 3: Densities of the bodies in the Solar System

Fig. 10: Model of densities

Minerals	Density	Other materials	Density
Plaster	2.3	Glycerin	1.3
Orthoclase	2.6	Cork	0.24
Sulfur	1.1-2.2	Aluminium	2.7
Alite	2	Iron	7.86
quartz	2.65	Cement	2.7 – 3.1
Borax	1.7	Glass	2.4 – 2.8
Blende	4	Tin	7.3
Pyrite	5.2	Clay	1.8 – 2.5
Erythrocytes	5.4	Bakelite	1.25
Calcite	2.7	Oak	0.90
Galena	7.5	Pinewood	0.55

Table 4: Examples of densities of some materials

From table 3 of planetary densities, simply compare with the densities of various minerals (in every school there is usually a collection of materials) or with samples of other materials that are easy to find such as glass, ceramics, wood, plastics, etc.. The following Table 4 presents some examples of materials and their densities.

When using materials not included in table 4, it is very easy to calculate its density. Simply take a portion of this material, weigh it to find its mass, *m*, and put it in a container of water to measure its volume, *V*. The density *d* of the material will be,

$$d = \frac{m}{V}$$

Students should notice that Saturn would "float" in water, because its density is less than 1.

Activity 8: Flattening model of planets

To visualize the deformation (flattening) of gas planets due to the centrifugal force generated by their rotation, we will build a simple model.

As we can see in figure 9, with a stick and some cardboard strips, we can build this simple model that reproduces the flattening of Solar System planets due to rotation.

1. Cut some cardboard strips 35 per 1 cm in size.
2. Attach both ends of the strips of cardboard to a 50 cm-long cylindrical stick. Attach the top ends to the stick so that they cannot move, but allow the bottom ends to move freely along the stick.
3. Make the stick turn by placing it between two hands, then rotating it quickly in one direction and then the other. You will see how the centrifugal force deforms the cardboard bands (figure 11) in the same way it acts on the planets.

Fig. 11: Model to simulate flattening due to rotation

Activity 9: Model about planetary orbital periods

The planets orbit the Sun with different speeds and orbital periods (table 5). Known the period and the average distance from the Sun can be deduced the mean orbital velocity of the planet to explore its orbit. See for example the case of Earth, but you can repeat the same reasoning to any other planet.

The length of an orbital revolution is L = 2 π R, so the average orbital velocity is v = L / T = 2 π R / T. For Earth, the period is 365 days, then v = 2,582,750 km / day = 107,740 km / h = 29.9km / s, where the distance from Earth to the Sun R = 150 10^6 km. We emphasize that the Sun also revolves around the galactic center with a speed of 220 km / s, or what is the same about 800,000 km / h.

Planet	Orbital period (days)	Distance from the Sun (km)	Orbital average speed (km/s)	Orbital average speed (km/h)
Mercury	87.97	57.9 10^6	47.90	172440
Venus	224.70	108.3 10^6	35.02	126072
Earth	365.26	149.7 10^6	29.78	107208
Mars	686.97	228.1 10^6	24.08	86688
Jupiter	4331.57	778.7 10^6	13.07	47052
Saturn	10759.22	1 430.1 10^6	9.69	34884
Uranus	30.799.10	2 876.5 10^6	6.81	24876
Neptune	60190.00	4 506.6 10^6	5.43	19558

Table 5: Orbital data of the Solar System bodies

The fastest is Mercury, the closest to the Sun, and the slowest is Neptune, the most distant one. Romans had already noticed that Mercury was the fastest of all and so it was identified as the messenger of the gods and represented with winged feet. An orbital period or a ‘year’ on Mervcury lasts only 88 days. Even if observing with the naked eye, over several weeks it is possible to tell that Jupiter and Saturn move much more slowly across the zodiacal constellations than do Venus and Mars, for example.

Fig. 12a, 12b and 12c: Simulating the circular movement of planets.

There is also a simple way to experience the relationship between distance and orbital period.

We begin by tying a heavy object, such as a nut, onto a piece of string. Holding the string from the end opposite the heavy object, we spin the object in a circular motion above our heads. We can then see that if we release string as we spin it (making the string longer), the object takes longer to complete an orbital period. Conversely, if we take in string (making it shorter), it takes less time

We can then develop a solar system model with nuts and bits of string proportional in length to the radii of the planetary orbits (assuming, again, that they all travel in circular orbits). However, instead of cutting a separate piece for each planet, cut all pieces to a length of about 20 cm. Then, using the appropriate scaling, measure the correct distance from the heavy object and make a knot at this point. Then, the string can be held at the location of the knot while spinning the heavy object.

To use the model we must hold one of the strings at the location of the knot and turn it over our heads in a plane parallel to the ground with the minimum speed possible speed that will keep it in orbit. We will see that the object needs less time for a full rotation when the radius is smaller.

Model of surface gravities

The formula for gravitational force, $F = G\frac{Mm}{d^2}$, allows us to calculate the surface gravity g that acts on the surface of a planet with mass M. Considering a unit mass (m = 1) on the planet's surface (d = R, the planet's radius), we obtain the surface gravity $g = \frac{GM}{R^2}$, where G = 6.67 x10^{-11} m^3 kg^{-1} s^{-2} is the universal gravitational constant. If we then substitute the planet mass by $M = 4/3\ \pi R^3 \rho$, where ρ is the planet's density and R its radius, we find:

$$g = 4/3\ \pi G \rho R$$

Substituting these last two variables for the values listed in table 6 (after converting the radius to meters and the density to kg/m^3, with 1000 kg/m^3 = 1 g/cm^3), we can calculate the value of the surface gravity g for all planets.

Planet	R equatorial radius (km)	ρ density (g/cm^3)	g surface gravity (m·s^{-2})
Moon	1738	3.3	1.62
Mercury	2439	5.4	3.70
Venus	6052	5.3	8.87
Earth	6378	5.5	9.81
Mars	3397	3.9	3.71
Jupiter	71492	1.3	24.8
Saturn	60268	0.7	8.96
Uranus	25559	1.2	8.69
Neptune	25269	1.7	11.00

Table 6: Size, density and surface gravity of Solar System bodies.

Let's see a couple of examples:

$$g_{mercury} = 4/3\ \pi\ G \cdot\ 2439 \text{ x } 10^3 \text{ m} \cdot 5400 \text{ kg/m}^3 = 3.7 \text{ m/s}^2,$$
$$g_{venus} = 4/3\ \pi\ G \cdot 6052 \text{ x } 10^3 \text{ m} \cdot 5300 \text{ kg/m}^3 = 8.9 \text{ m/s}^2.$$

Similarly, we can calculate g for the rest of the planets. As in table 7, surface gravities are often given relative to the Earth's, and indicated by the letter g

Activity 10: Model of bathroom scales

In this case, the goal of the model is to develop a set of 9 bathroom scales (8 planets and the Moon) so that students can simulate weighing themselves on each of the planets and the moon.

Since the process is the same for each planet, we will only describe one of them. The idea, essentially, is to open up a bathroom scale and replace the disk labeled with weights with another with weights calibrated for a particular planet.

1. First, we open the scale. In most scales, there are two springs that secure the base. Remember that we have to put it back together again (figures 13a y 13b).
2. Once open, the weight disk should be removed, either to be replaced, or drawn over with the appropriate planetary weights.
3. In the following table we have surface gravities of the Moon and various planets of the Solar System. In one column, they are listed in absolute values (m·s^{-2}), and in the other in relative values with respect to terrestrial gravity. These values are the ones we will use to convert units of "terrestrial" weight to proportional units of weight on other planets.
4. Finally, we close the scale again, and can now see what we would weigh on one of the planets.

	g surface gravity ($m \cdot s^{-2}$)	g surface gravity (relative to Earth)
Moon	1.62	0.16
Mercury	3.70	0.37
Venus	8.87	0.86
Earth	9.81	1.00
Mars	3.71	0.38
Jupiter	24.79	2.53
Saturn	8.96	0.91
Uranus	8.69	0.88
Neptune	11.00	1.12

Table 7: Absolute and relative surface gravities for Solar System bodies.

Fig.13a and 13b: Bathroom scale with the replaced disk.

Fig. 14: Solar System model with bathroom scales.

Activity 11: Models of craters

Most craters in the solar system are not volcanic but are the result falling meteoroids onto the surfaces of planets and satellites.

1. First, cover the floor with old newspapers, so that it doesn't get dirty.
2. Put a 2-3 cm layer of flour in a tray, distributing it with a strainer/sifter so that the surface is very smooth.
3. Put a layer of a few millimeters of cocoa powder above the flour with the help of a strainer/sifter (figure 15a).
4. From a height of about 2 meters, drop a projectile: a tablespoon of cocoa powder. The fall leaves marks similar to those of impact craters (figure 15b).
5. You may want to experiment with varying the height, type, shape, mass, etc. of the projectiles. In some cases, you can get even get a crater with a central peak.

Fig. 15a: Simulating craters.

Fig. 15b: Resulting craters.

Escape velocities

The escape velocity depends on the shape of the gravitational potential in which the projectile is located. Therefore, on the surface of a celestial object, the escape velocity depends only on the height of the launch point, if the frictional forces in the atmosphere, if it were present (such is the case of the Earth)

The escape velocity does not depend on the mass of the projectile or the direction of the launch, and its deduction can be made in purely energetic terms.

To calculate the escape velocity, the following formulas related to the potential energy and kinetic energy are used:

$$E_c = \frac{1}{2}mv^2 \qquad E_p = -G\frac{Mm}{R}$$

Considering the principle of conservation of energy, if we establish the condition that the object moves away to an infinite distance and remains at rest, it results:

$$\frac{1}{2} m v_e{}^2 - G\frac{Mm}{R} = 0$$

and clearing the speed::

$$v_e = \sqrt{\frac{2GM}{R}} = \sqrt{2gR}$$

where: v_e is the escape velocity, G is the universal gravitation constant (6.672×10^{-11} N m^2/kg^2), M is the mass of the star, m is the mass of the projectile, R is the radius of the star (in the assumption of spherical shape), g is the acceleration of gravity on the surface of the star. On Earth, g = 9.81 m/s^2.

As an example, we calculate the escape velocities of some planets. For the Earth,

$$v_{earth} = \sqrt{2gR} = (2 \cdot 9.81 \text{ m s}^{-2} \cdot 6378 \text{ x } 10^3\text{m})^{1/2} = 11186 \text{ m/s} \approx 11.2 \text{ km/s..}$$

Similar, for the smallest planet, Mercury,

$$v_{mercury} = (2 \cdot 3.78 \text{ m s}^{-2} \cdot 2439 \text{ x}10^3\text{m})^{1/2} = 4294 \text{ m/s} \approx 4.3\text{km/s.}$$

And for the greatest planet, Jupiter,

$$v_{jupiter} = (2 \cdot 23.1 \text{ m s}^{-2} \cdot 71492 \text{ x}10^3\text{m})^{1/2} = 57471 \text{ m/s} \approx 57\text{km/s.}$$

It is clear that it is easier to launch a rocket from Mercury than from the Earth, but it is most difficult to launch a rocket on Jupiter, where the escape velocity is about 60 km / s.

(To be able to compare the results, the accepted escape velocity for each body in the Solar System are the following: Mercury 4.3 km/s, Venus 10.3 km/s, Earth 11.2 km/s, Mars 5.0 km/s, Jupiter 59.5 km/s, Saturn 35.6 km/s, Uranus 21.2 km/s, Neptune 23.6 km/s. As we can see, our simple calculations give us acceptable results.)

Activity 12: Model of a rocket with an effervescent tablet

As an example of a rocket that can be launched safely in the classroom, we propose the following rocket, which uses an aspirin or effervescent tablet as a propellant. We begin by cutting out the rocket model on the solid lines, and pasting on the dotted lines like in the photo.

We will use a plastic capsule, such as used to store pills or food for fish, making sure that the capsule can fit inside the cylinder of the rocket. Then, we put the three triangles as supports on the body of the rocket and finally, add the cone on the top of the cylinder (figures 16a, 16b, 16c, 16d, 17, 18, 19a, 19b, 19c)

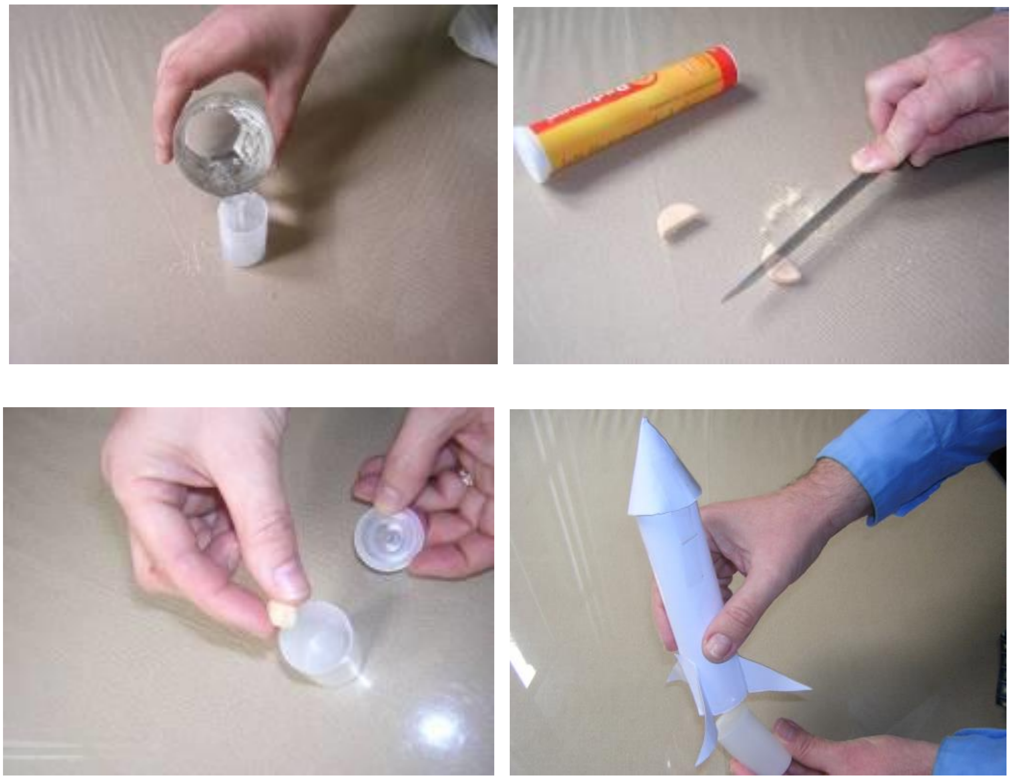


Fig. 16a, 16b, 16c and 16d: The process in four pictures.

After constructing the rocket, we have to carry out the launch. For this, we will put water into the plastic capsule, up to about 1/3 of its height (about 1 cm). Add 1/4 of an effervescent aspirin tablet (or other effervescent tablet). Put the tape and the rocket above the capsule. After about 1 minute, the rocket takes off. Obviously we can repeat as many times as we would like (at least 3/4 of the aspirin tablet remains, so enjoy launching rockets!).

It is also possible to lanch rockets using bicarbonate and vinager.

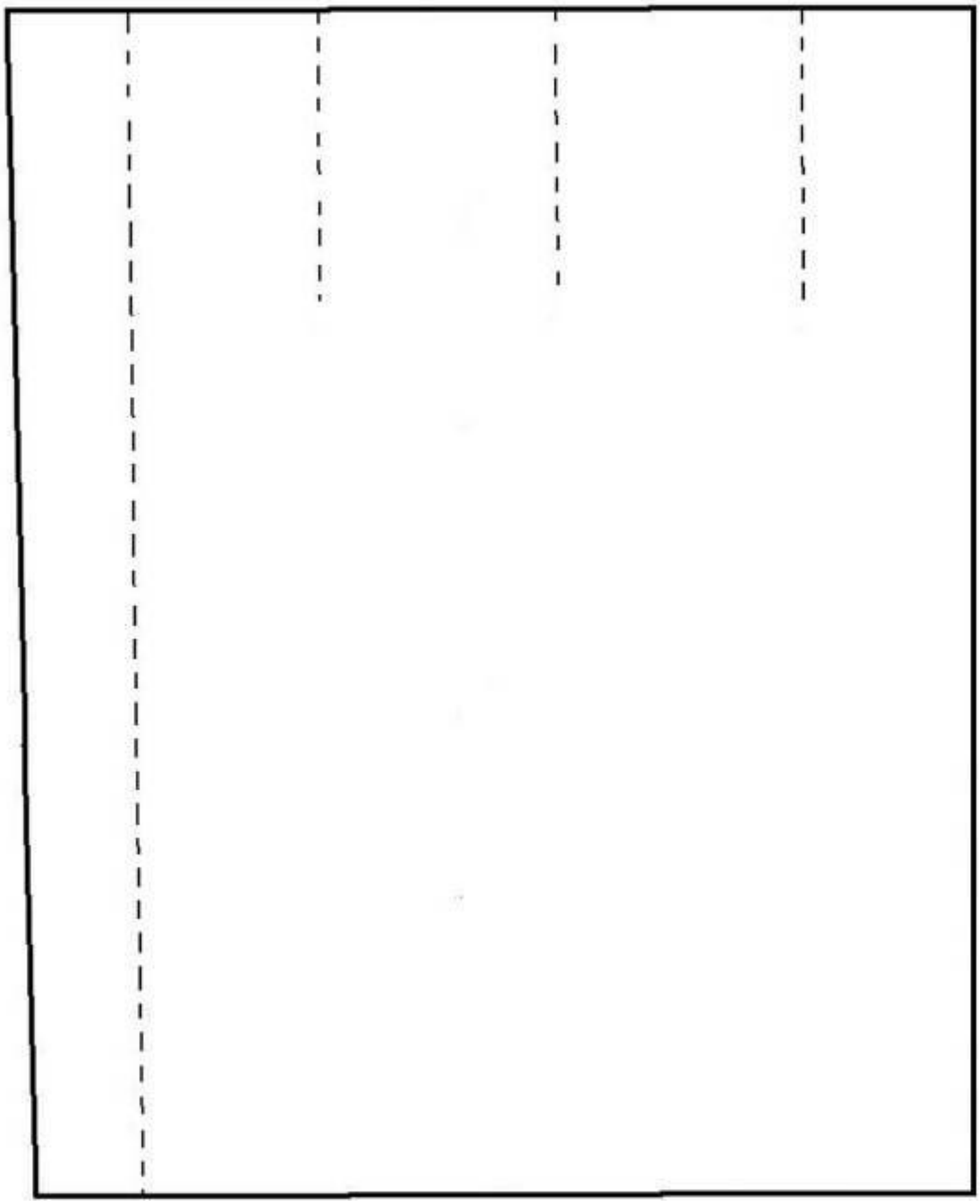


Fig. 19a: Body of the rocket. Paste the fins in the dotted zone.

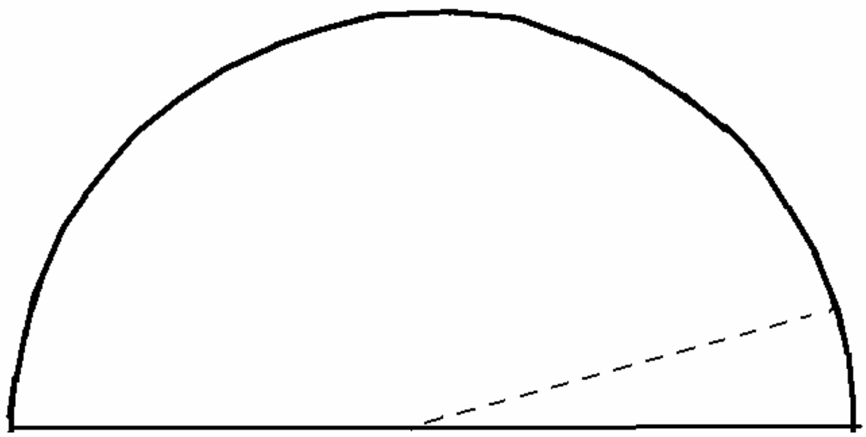
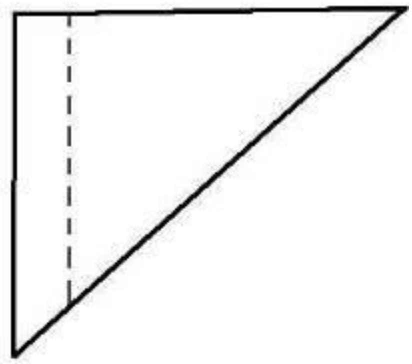


Fig. 19b: Top cone of the rocket.



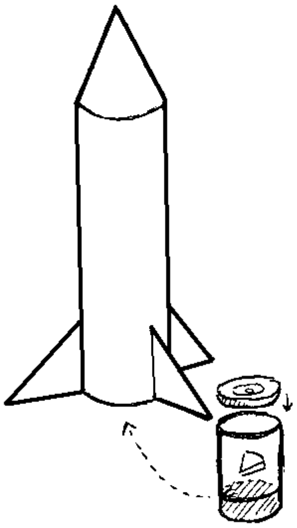


Fig. 19c: Model for the three fins. Fig. 18: Simplified scheme Fig. 19: Spme rockets.

Exoplanets

So far, astronomers have detected about 4000 planets and 500 multiple planetary systems. An example of one of the first planets photographed directly is shown in figure 20.

All the topics of this workshop are part of the technological evolution that allows advances in this area. Some aspects may be less important in the future but it is good to take them to schools. This is a fast-moving field and some content might need to be updated.

Let's consider an example from the history of astronomy. In 1610 Galileo observed Saturn for the first time. He did not understand that the object was a planet surrounded by a fine ring.

Instead he interprets it as a star cluster with three components. We have to wait for Huygens' observations with a better telescope to resolve the planet and ring system. For a few years the scientific community misinterpreted the structure of Saturn. An example of this is seen in Rubens' painting of 1636-1638, which represents Saturn as three stars following its recent discovery by Galileo.

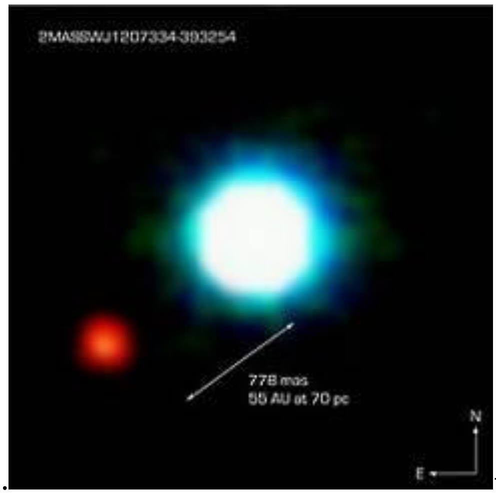


Fig. 20: The first planet (2M1207b) observed directly, on March 16, 2003 with one of ESO's 8 m VLT telescopes. It has a mass of 3-10 times of the Jupiter and it orbits at 41 AU from its central star which is a brown dwarf. In 2006, a dust disk was found around the central star, providing evidence of the continuing planet formation in this young system (Source: ESO).

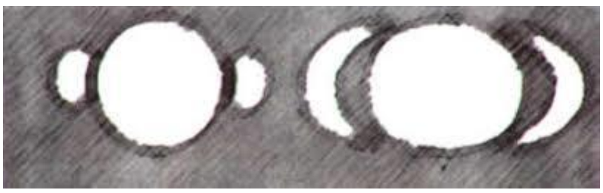


Fig. 21a and 21b: Saturn according to Rubens (1636-1638) and drawing made by Galileo in 1610.

In this same vein it is good to remember that Ceres was considered to be planet in the 19th century (from 1801 to 1850), but it was later classified as an asteroid. In the same way when Pluto discovered in 1930 it was classified as a planet. However, in 2006 it was reclassified as a minor planet as was Ceres. So surely some of the current understanding of exoplanets may need to be reconsidered in the future, but this should not stop us from introducing this topic into educational centres.

Nomenclature of the exoplanets

An extrasolar planet or exoplanet is considered to be a planet that orbits a star other than the Sun and, therefore, does not belong to our solar system. NASA maintains a catalogue (http://exoplanetarchive.ipac.caltech.edu/) with more than 4000 confirmed exoplanets in 2019. The nomenclature of the exoplanets is simple and comes from its use in binary stars. A lowercase letter is placed after the name of the star from the letter "b" for the first planet found in the system (for example: 51 Pegasi b). The next planet detected in the system is labelled with the following letter of the alphabet c, d, e, f, etc. (for example: 51 Pegasi c, 51 Pegasi d, 51 Pegasi e or 51 Pegasi f). Thus, the order of the letters has nothing to do with the orbital period of the planets, or with other parameters. In addition, in 2015 the International Astronomical Union (IAU) assigned names to the first 19 discovered exoplanetary systems. Thus, in the Upsilon Andromedae star system (see Table 8), the main star (Ups And) has the alternative name of *Titawin*, and the planets b, c and d will be called *Saffar, Samh* and *Makriti*. But at present, these names have not come into use either in the community of professional or amateur astronomers.

Detection of exoplanetary systems

The distance to Alpha Centauri or Proxima Centauri, the closest stars to us that are only 4.5 light years away, is enormous compared to the distance of the planets in our solar system. In fact, Alpha Centauri is about 10 000 times farther than Neptune, our most distant planet. These enormous distances made the detection of planets around other stars impossible until sophisticated observational techniques were developed near the end of the last century.

The third brightest star in the night sky is Alpha Centauri. Alpha Centauri is, in reality, a triple star system. It consists of a binary pair, Alpha Centauri A and B, and a dwarf star closest to us, called Proxima Centauri. It is around this third star, of the “red dwarf” type, where a rocky planet has been detected that may have some similarities with the Earth: Proxima b, which is how the new exoplanet has been named, the closest to Earth that is known but it has not been directly observed. Those responsible for the discovery revealed its presence by observing a small anomaly in the orbit of the star, caused by the gravitational influence of the planet. This disturbance has served to deduce the presence of the planet and some of its characteristics. It goes around its sun in just 11 days, it is slightly larger than Earth and probably has a solid surface.

A significant feature of this exoplanet is its proximity to its parent star, Proxima Centauri. It is 5% of the distance that separates the Earth from the Sun, that is, about 0.05 AU. This proximity would make it a burning hell if its star were like our Sun. However its sun is a red dwarf and so the planet is in the habitable zone. This is because a red dwarf like Proxima Centauri, with 12% of the solar mass, has a brightness of only 0.1% of the Sun. With these characteristics, the new planet would have a temperature of 40 degrees below zero without the greenhouse effect of a possible atmosphere, which could raise the temperature a few degrees above the freezing point of water.

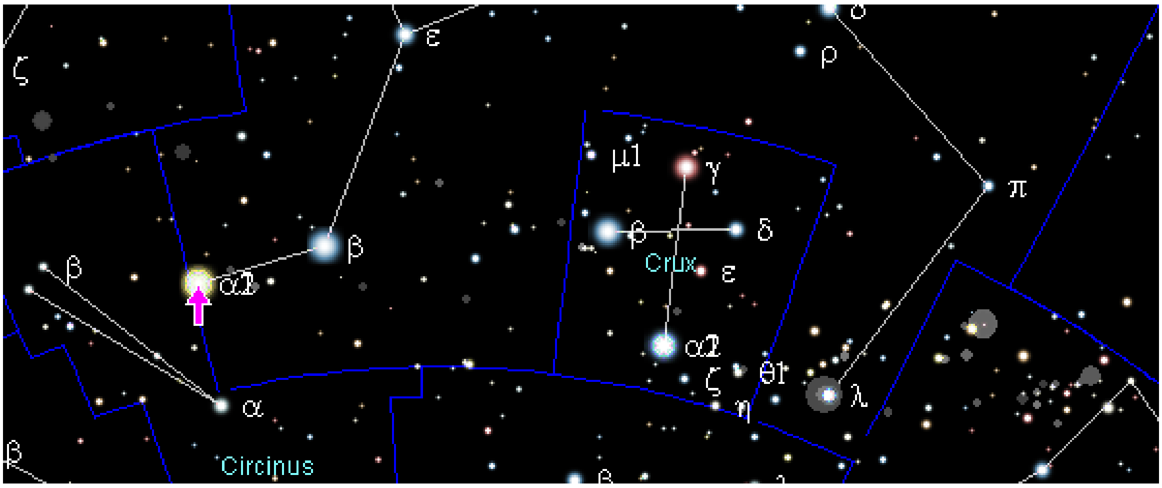


Fig. 22: Alpha Centauri near the Southern Cross.

One of the drawbacks for the presence of life in these planetary systems around a red dwarf is that the planets have to be very close to their star to have a temperature at which water can exist in a liquid state. When that happens, in many cases there is a phenomenon called synchronous rotation that we see in our own Moon. The orbital time and the rotation time are equalized and the planet always shows its same face to the star. This would suggest a scorched hemisphere in which the atmosphere evaporated and the other frozen. However, an atmosphere denser than Earth's would allow for these extreme temperatures to be moderated through atmospheric circulation and redistribution of heat.

Radial velocity method

At present, there are two methods that are dominating the discovery of exoplanets. Both are indirect methods, in which the presence of a planetary system is inferred from the observation of the central star of the system.

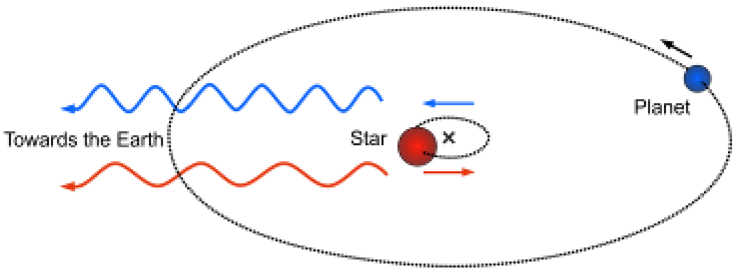


Fig. 23: Radial velocity method for the detection of planets.

The radial velocity method found the first exoplanet revolving around a central star, with the discovery of 51 Pegasus b in 1995. In this method, the wobble of the central star is measured due to the planet's movement around the central star. The star and the planet orbit the barycentre of the star-planet system. This movement of the central star induces very small changes in the star's light from red to blue (figure 23), due to the Doppler shift. In this way, we can determine the mass of a planet with respect to the mass of the central star. In practice, however, we do not know the orientation of most of the planet systems detected with this method hence the masses of the planets that we can extract are minimum masses (which means that the real masses could well be larger).

Activity 13: The Doppler Effect

As seen in the Expansion of the Universe workshop, the Doppler Effect is what makes the wavelength of a sound vary when the source is in motion. It can be demonstrated by rotating an alarm clock inserted in a cloth bag tied with a rope in a horizontal plane. When it approaches the listener wavelength is shortened and the sound has a higher pitch. When it moves away, the wavelength lengthens and the sound has a lower pitch. The person at the centre of rotation does not detect any variation.

In the case of the exoplanet and star, the light waves from the star are affected. When a star approaches us, the apparent wavelength of its radiation decreases, its light shifts towards the blue end of the visible spectrum. When the star moves away, the apparent wavelength increases and its light shifts towards the red end of the visible spectrum.

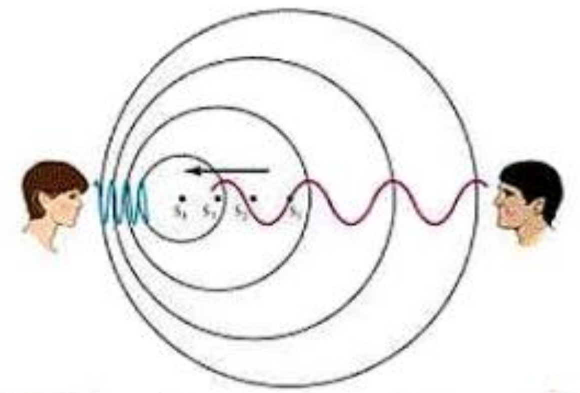


Fig. 24: When the source approaches the wavelength decreases and when the source moves away the wavelength increases.

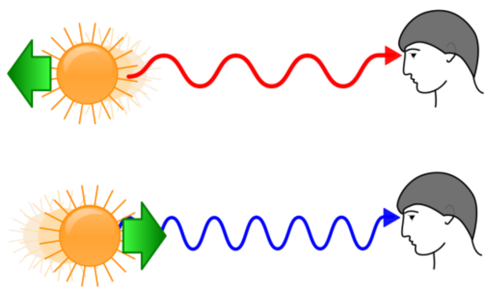


Fig. 25: When the source approaches it seems bluer and when the source moves away it seems redder.

This is the Doppler Effect due to relative motion and it is what exoplanets have when they move around the parent star. When the exoplanet moves away from us its light moves towards red and when it approaches its light moves towards blue.

Transit Method

The other important method, called "transit method" is based on the observation of changes in the brightness of a star when one of its planets passes ("transits") in front of the star, thereby hiding a small part of its disk stellar (figure 26). With the transit method, the size of a planet, *Rp*, can be measured in relation to the size R_* of its central star, and is approximately given by:

$$Rp / R_* = \sqrt{dF / F}$$

where *dF / F* is the relative change in brightness observed during the transit of a planet (for example, *dF / F = 0.01* indicates a 1% reduction in the star's brightness during transit).

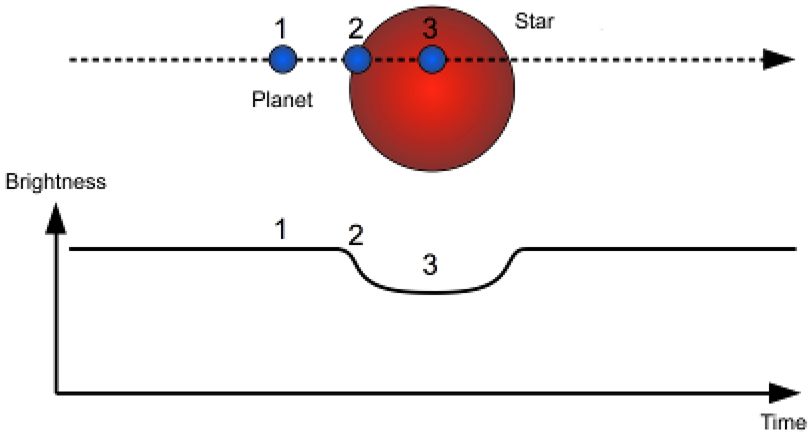


Fig. 26: Transit method for the detection of planets.

Activity 14: Transit simulation

A transit can be simulated using two balls: a large one that represents the star and a small one that represents the planet orbiting the central star. If observers are in the same plane as the orbit of the planet and are observing at that moment, they will know when the planet passes in front of the star by the fall and rise in the luminosity curve of the star (figure 27). But it is clear that if the observer is not in the same plane of rotation, no change in the brightness curve will be observed (figure 28).

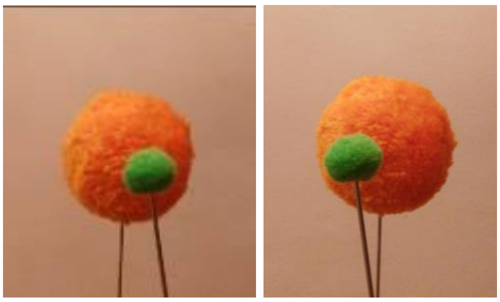


Fig. 27: Observer in the plane of rotation can see the transit of the planet and detect the changes in the

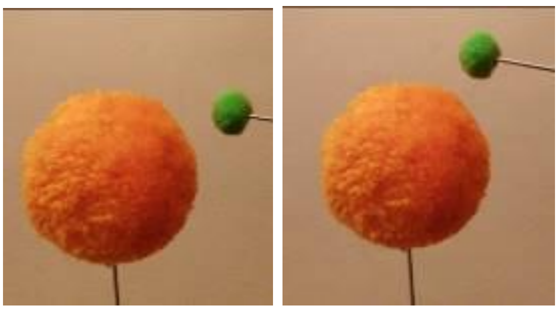


Fig. 28: Observer outside the plane of rotation, cannot view any change in the brightness curve.

Microgravitational Lens Method

Other methods of exoplanet detection also stand out, although they are less used. The method of microgravitational lenses consists in observing an increase in the brightness of a background star, due to the alignment of the background star with a star with exoplanets. The exoplanetary system acts as a gravitational lens and would generate a very characteristic brightness extension (red line in figure 29). For it to work, there must be complete visual alignment between the three parts (background star, star with exoplanet and Earth).

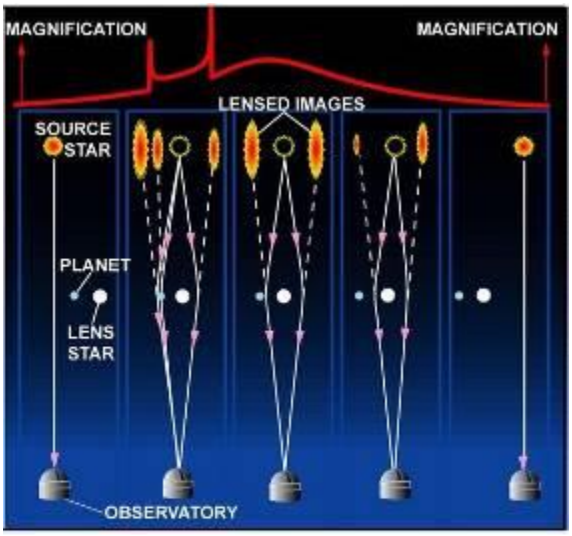


Fig. 29: Method of microlensing for the detection of planets.

Activity 15: Simulation of microlenses

You can simulate the detection of an exoplanet around a parent star with a pair of wine glass bases, as used in the Expansion of the Universe workshop. First we use only one base and nothing is seen. Then we pass the other one and a point emerges and then perhaps even two.

Fig. 30: First with only one lens.

Fig. 31: Moving the second lens over the first, a point appears and then two, in all cases without moving the first lens.

Direct detection method

And finally, the direct detection method corresponds to the acquisition and analysis of very high-resolution images of the star, in order to determine the existence of planets around it. Due to the amount of light emitted by a star, this method has been successful only for planets that are very far from their central star and at the same time are very young, so they still emit light due to the heat generated during their formation (see also figure 32).

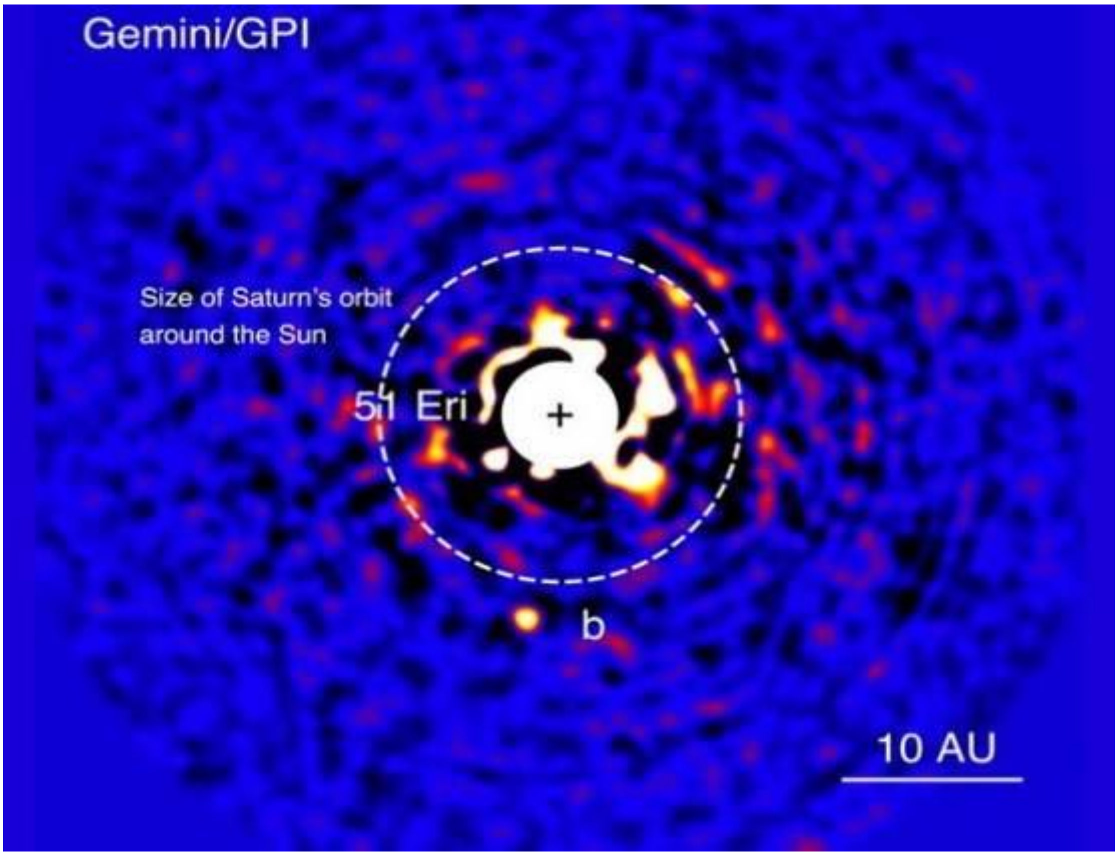


Fig. 32: Direct detection method for the detection of planets.

Examples of extrasolar systems

The best-known exoplanets have masses comparable to Jupiter, which is the largest planet in our solar system. This is why the masses and sizes of extrasolar planets in mass units of Jupiter M_J (1.90 x 10^{27} kg) and radius of Jupiter R_J (71492 km) are often indicated. Only very few planets (around 20) are known to have masses comparable to Earth. However, there are more planets (around 700, or 20% of all known) with sizes comparable to Earth, up to 1.5 Rt (terrestrial radii). It has been shown that these planets are the most common, but current detection techniques are more successful in detecting more massive or larger objects.

Planet Name	Average distance AU	Orbital period days	Minimum mass * Jupiter or Terrestrial Mass	Discovered year	Radius km
Ups And b	0,059	4,617	0,69 Mj	1996	124000*
Ups And c	0,83	241,5	1,98 Mj	1999	176000*
Ups And d	2,51	1274,6	4,13 Mj	1999	221999*
Ups And e	5,24	3832,5	1,06 Mj	2010	70000*
Gl 581 e	0,030	3,149	1,9 Mt	2009	7600*
Gl 581 b	0,041	5,368	15,7 Mt	2005	16000*
Gl 581 c	0,073	12,932	5,7 Mt	2007	11000*
Kepler-62 b	0,0553	5,714	9 Mt	2013	8350
Kepler-62 c	0,0929	12,441	4 Mt	2013	3400
Kepler-62 d	0,120	18,164	14 Mt	2013	12400
Kepler-62 e	0,427	122,387	1,6 Mt	2013	10300
Kepler-62 f	0,718	267,291	2,8Mt	2013	9000
Trappist-1 b	0,012	1,5111	1,02 Mt	2016	7100
Trappist-1 c	0,016	2,422	1,16 Mt	2016	7000
Trappist-1 d	0,022	4,050	0,30 Mt	2016	5000
Trappist-1 e	0,030	6,099	0,77 Mt	2017	5800
Trappist-1 f	0,039	9,206	0,93 Mt	2017	6700
Trappist-1 g	0,047	12,354	1,15 Mt	2017	7300
Trappist-1 h	0,062	18,768	0,33 Mt	2017	4900

Table 8: Four representative extrasolar systems with multiple planets. Data extracted from the *Extrasolar Planets Catalogue 2* (except the last column). * These planets have been discovered by radial velocity; that is why there is no certainty of their sizes. For giant planets, with masses of 0.5-20 Mj, it is known that almost all of them have a radius of 0.7-1.4 times that of Jupiter (50-100 thousand kilometres), with little correlation with their mass. For the terrestrial planets of the GJ861, its radius has been calculated assuming that the density of the planet is equal to the density of the Earth (5520 kg/m^3).

In this section, we consider some examples of extrasolar planetary systems that have three or more known planets. Table 3 shows the planets around the stars Ups Andromeda, Gliese 581, Kepler-62 and Trappist-1. The planetary systems of Ups Andromeda and Gliese 581 were discovered using the radial velocity method and of these planets we know only their minimum masses, but not their sizes. Their radii are considered to be between 50000-100000 km (although Table 1 shows one of the possible values). For Gliese 581, several other planets (d, f, g) have been announced, but were contradicted in other publications; so their discovery has been retracted. It was probably caused by marginal signals or noise from other sources in the data.

The planets of the Kepler-62 system were discovered from transits. Therefore, their sizes are known. Of their masses we only know upper limits (maximum masses) and they are too small (and light in weight) to be detectable with the radial velocity method. However, there are also many planets that have been detected with both the transit and the radial velocity method and we know both their masses and their sizes.

There are some exoplanets that are very close to the central star (e.g. all the planets of the Gliese 876 have orbits closer to the star than Mercury to the Sun). Others have more distant planets, such as the 2M1207b system (see Fig. 1), with a planet in formation at 41 AU away, or 1.4 times the distance of the Neptune. One of the possibilities to visualize this data is to build scale models of the chosen planetary system. This will allow us to easily compare with each other and with our Solar System.

Planet Name	**Average distance** AU	**Orbital Period** years	**Mass**, Jupiter Mass	**Radius** km
Mercury	0.3871	0.2409	0.0002	2439
Venus	0.7233	0.6152	0.0026	6052
Earth	1.0000	1.0000	0.0032	6378
Mars	1.5237	1.8809	0.0003	3397
Jupiter	5.2026	11.8631	1	71492
Saturn	9.5549	29.4714	0.2994	60268
Uranus	19.2185	84.04	0.0456	25559
Neptune	30.1104	164.80	0.0541	25269

Table 9: Solar System Planets.

Currently we know that there are also exoplanets around stars very different from the Sun. In 1992 radio astronomers announced the discovery of the first exoplanet, around the PSR 1257 + 12 pulsar. It took three more years to discover the first exoplanet around a "normal" solar-type star, 51 Pegasi. Afterwards, exoplanets have been detected around: red dwarfs (eg Gliese 876 in 1998), giant stars (Iota Draconis in 2001), brown dwarfs (2M1207 in 2004), type A stars (Fomalhaut in 2008, see figure 33), white dwarfs (WD1145-1017 in 2015, with a disintegrating planet), around binary systems (Kepler-16b in 2011), among others.

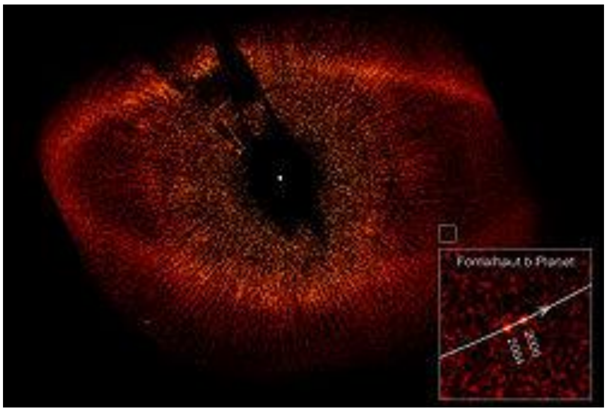


Fig. 33: Planet Fomalhaut b within the interplanetary dust cloud of Fomalhaut in an image of the Hubble Space Telescope, with positions in 2004 and 2006 (see small image). (Photo: NASA)

Activity 16: Models of exoplanetary systems

First we choose the scale of the model. It is not convenient to use the same scale for diameters and distances due to a size problem. For distances, the scale considered is: 1 AU = 1 m. In this case all exoplanets can fit inside a typical classroom, as well as the first five planets of our solar system. For the size scale for the planet, a radius of the planet of 10,000 km corresponds to a diameter of the model of 0.5 cm. In this case, the largest planet, Jupiter, with a radius of 71,000 km is 7 cm in diameter and the smallest, Mercury, will be 0.2 cm. If the activity is carried out outside (for example, in the schoolyard), we can build a complete model with similar scales for diameters and distances. For the parent stars the same scale is, a radius of the parent star of 10 000 km corresponds to a diameter of the model of 0.5 cm.

Solar System	Distance	Radius km	Model Distance	Model Diameter
Mercury	0.39 AU	2439	40 cm	0.1 cm
Venus	0.72 AU	6052	70 cm	0.3 cm
Earth	1 AU	6378	1.0 m	0.3 cm
Mars	1.5 AU	3397	1.5 m	0.1 cm
Jupiter	5.2 AU	71492	5.0 m	3.0 cm
Saturn	9.55 AU	60268	10 m	2.5 cm
Uranus	19.22 AU	25559	19 m	1.0 cm
Neptune	30.11 AU	25269	30 m	1.0 cm

Table 10: Solar System. The parent star, the Sun is G2V, with a diameter in the model of 35 cm. Habitability zone indicated in green.

Under the expressed conditions of scale, the Solar System is constructed (Table 10), or any of the systems in Table 1 using the radii and the average distance values included in the table. To simplify the process, the tables with the aforementioned scale are included below.

It begins with the first planetary system that was discovered in 1999 by detecting its planets by Doppler Effect applied to the radial velocity of the star. This method, due to the level of technology, allows to detect very large exoplanets that are close to the parent star. No doubt the detection method also determines the characteristics of the located planets. With this detection method, gaseous planets such as Jupiter or even much larger have been located. To locate planets that could support life, it was necessary to try to detect smaller, terrestrial planets like Earth.

Upsilon Andromedae Titawin	Distance AU	Diameter km	Model Distance	Model Diameter
Ups And b / Saffar	0.059 AU	108000	6 cm	5.5 cm
Ups And c / Samh	0.830 AU	200000	83 cm	10.0 cm
Ups And d / Majriti	2.510 AU	188000	2.5 m	9.5 cm
Ups And e / Titawin e	5.24 AU	140000	5.2 m	7.0 cm

Table 11: Parent star Upsilon Andromedae is a star F8V at 44 light years in the constellation Andromeda. It is a binary star composed of Ups And A, a star quite similar to the Sun but somewhat hotter and brighter, with a

radius of 1.28 Rsun and Ups And B which is a small red dwarf. In the Ups And A model it has a diameter of 45 cm.

Gaseous planets are considered to be unable to support life in the sense that we know it so there is a tendency to study rocky planets of Earth type instead of Jupiter planets which were the first to be discovered.

Gliese 581 is one of the first systems where it was possible to detect exoplanets of the terrestrial type. Although since 2014 some of its exoplanets have been discussed. The detection method considered in this case was that of radial velocities but due to the low mass of the GL 581 of 0.31 Msun, it was possible to find terrestrial exoplanets.

Gliese 581	Distance AU	Diameter / km	Model Distance	Model Diameter
Gliese 581 e	0.030 AU	15200	3 cm	0.8 cm
Gliese 581 b	0.041 AU	32000	4 cm	1.6 cm
Gliese 581 c	0.073 AU	22000	7 cm	1.1 cm

Table 12: The parent star Gliese 581 is a red dwarf M2.5V located at 20.5 ly in Libra constellation. It has a third of the mass of the Sun and is less luminous and colder than it. Its radius is 0.29 Rsun and in the model it corresponds to a diameter of 10 cm

In 2009, the Kepler mission was launched. This space observatory orbits the Sun and seeks extrasolar planets, especially those of similar size to Earth that are in the habitable zone of their parent star. In the 9 years that the mission lasted about 3000 exoplanets were detected and there are still thousands of candidates waiting to be confirmed. Kepler swept 0.25 percent of the sky and its findings showed that planets are very common in the Milky Way. In 2018, the TESS satellite was launched. It is designed to identify nearby planets with a size no larger than twice the Earth and in a much wider area of the sky that will cover 85 percent of the celestial vault. Both Kepler and TESS have been designed to explore the sky in search of planetary transits.

Kepler 62	Distance AU	Diameter / km	Model Distance	Model Diameter
Kepler 62 b	0.056 AU	33600	5.5 cm	1.7 cm
Kepler 62 c	0.093 AU	13600	9 cm	0.7 cm
Kepler 62 d	0.120 AU	48000	12 cm	2.4 cm
Kepler 62 e	0.427 AU	40000	43 cm	2.0 cm
Kepler 62 f	0.718 AU	36000	72 cm	1.8 cm

Table 13: Parent star Kepler 62 is a star F2V, in the constellation Lyra at 1200 ly. It is a star slightly colder and smaller than the Sun. Its radius is 0.64 Rsun and in the model it corresponds to a diameter of 22 cm

Kepler-62 is one of the most interesting examples of a potentially habitable planet system. Of particular interest are the planets e and f, since they are the best candidates for solid planets that fall into the habitable zone of their star. Their radii, 1.61 and 1.41 terrestrial radii, respectively, place them in the radius range of what may be solid terrestrial planets and fall within the habitable zone of Kepler-62: and at a range of distance at which these two planets could have liquid water on their surfaces, perhaps covering them completely. For Kepler-62e, which is located near the inner edge of the habitable zone, this would require reflective cloud cover that reduces the radiation that heats the surface. Kepler-62f, on the other hand, is located in the outer zone of the habitable zone, just like Mars in our solar system. There, significant amounts of carbon dioxide are required to keep a planet's surface warm with enough water for the surface of the liquid.

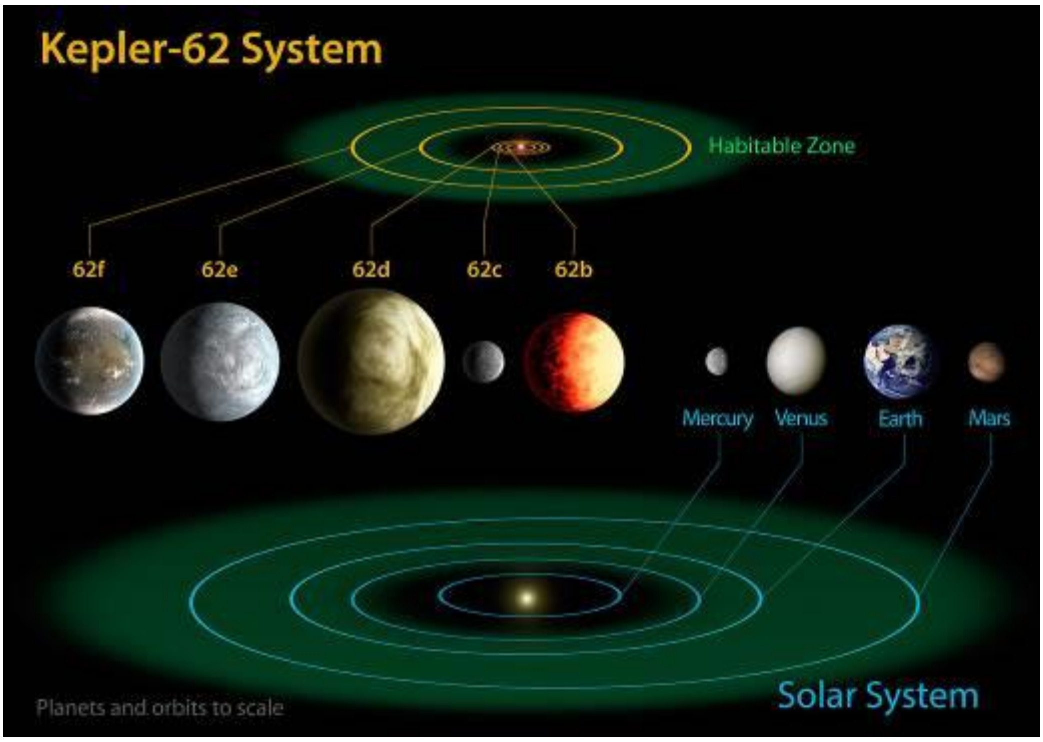


Fig. 34: The Kepler-62 system compared to the indoor solar system. The green region indicates the habitable zone - the area where life as we know it could exist. Source NASA Ames / JPL-Caltech.

A nearby red dwarf, listed as 2MASS J23062928-0502285 was tracked in transits in 2015 with the Trappist telescope, initially discovering about three planets of terrestrial sizes, baptized Trappist-1b, c and d. Later studies carried out by international teams using the Hubble, Kepler, Spitzer and Telescope telescopes in Chile, allowed us to better understand a total of seven planets. Five of these planets (b, c, e, f and g) are similar in size to Earth, and two (d and h) are of intermediate size between Mars and Earth. Three of the planets (e, f and g) orbit within the habitable zone.

The TRAPPIST-1 planets all orbit very close to their star and pass so close to each other that the gravitational interactions are significant and their orbital periods are almost resonant. The planets would appear prominent in the skies of their neighbours, and in some cases, several times larger than the Moon appears from Earth. In fact, their masses have not been determined with radial velocities but with the deviations in the periodicity of their orbits, using a method called 'transit timing variations' (transit time deviations).

The masses of all of them could be obtained with a very small margin of error, which allowed to determine with precision the density, the superficial gravity and their composition. The exoplanets have a mass range of approximately 0.3 Mt to 1.16 Mt, with densities of 0.62 to

1.02 terrestrial (3.4-5.6 g/cm^3). Planets c and e are almost totally rocky, while b, d, f, g and h have a volatile layer in the form of a water shell, ice shell or a thick atmosphere. Trappist-1d appears to have an ocean of liquid water that comprises approximately 5% of its mass, for comparison, the water content of the Earth is <0.1%, while the water layers of Trappist-1f and g are probably frozen. Trappist-1e has a slightly higher density than Earth, indicating a composition of terrestrial rock and iron. In addition, it was discovered that Trappist-1b's atmosphere was above the limit of the runaway greenhouse from 101 to 104 bar of water vapor. Planets c, d, e and f lack hydrogen-helium atmospheres. Planet g was also observed, but there was insufficient data to rule out a hydrogen atmosphere.

Trappist - 1	Distance AU	Diameter / km	Model Distance	Model Diameter
Trappist-1 b	0.012	14284	1.2 cm	1.4 cm
Trappist-1 c	0.016	13952	1.6 cm	1.4 cm
Trappist-1 d	0.022	9990	2.2 cm	1.0 cm
Trappist-1 e	0.030	11595	3.0 cm	1.2 cm
Trappist-1 f	0.039	13328	3.9 cm	1.3 cm
Trappist-1 g	0.047	14628	4.7 cm	1.5 cm
Trappist-1 h	0.062	9850	6.2 cm	1.0 cm

Table 14: The parent star Trappist-1 is a red M8V type dwarf located in the constellation Aquarius at 40 ly. It is a star slightly larger than Jupiter, with a diameter of 168,000 km and a diameter of 7 cm model. It is observed that the distances to the planets in the model are smaller than the diameter of the star, which gives an idea of the compactness of this system.

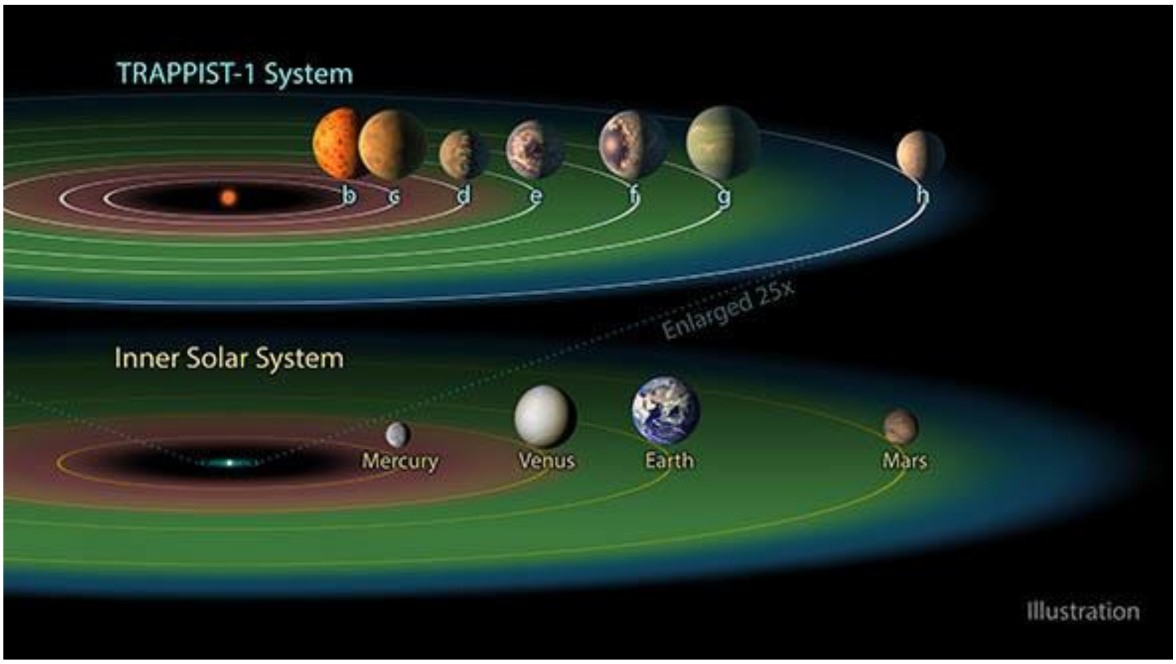


Fig. 35: The Trappist-1 system compared to the indoor solar system. The green region indicates the habitable zone - the area where life as we know it could exist.

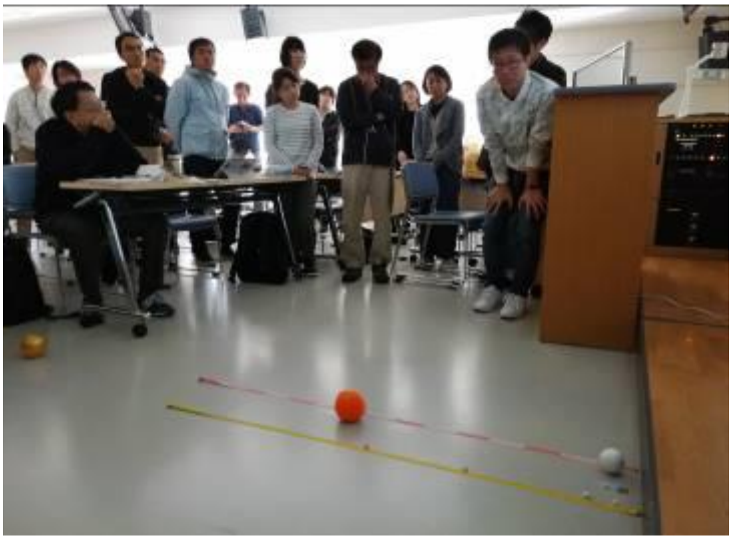


Fig. 36: Once all the models have been built, the points highlighted in the presentation of the habitability zone must be commented. Depending on the mass and type of parent star, the habitability zone is more or less close.

There are still many unanswered questions about the properties and habitability of exoplanets. Knowing more about them and learning more about their properties and characteristics has motivated several current and future space missions, such as NASA's TESS and JWST missions and ESA's CHEOPS and PLATO, the latter with the launch in 2026 and waiting for an expansion in the number of known terrestrial planets.

Bibliography

- Berthomieu, F., Ros, R.M., Viñuales, E., *Satellites of Jupiter observed by Galileo and Roemer in the 17th century*, Proceedings of 10th EAAE International Summer School, Barcelona, 2006.
- Gaitsch, R., *Searching for Extrasolar Planets*, Proceedings of 10th EAAE International Summer School, Barcelona 2006.
- Ros, R.M., *A simple rocket model*, Proceedings of 8th EAAE International Summer School, 249, 250, Barcelona, 2004.
- Ros, R.M., *Measuring the Moon's Mountains*, Proceedings of 7th EAAE International Summer School, 137, 156, Barcelona, 2003.
- Vilks I., *Models of extra-solar planetary systems, Proceedings of 10th EAAE International Summer School*, Barcelona 2006.