



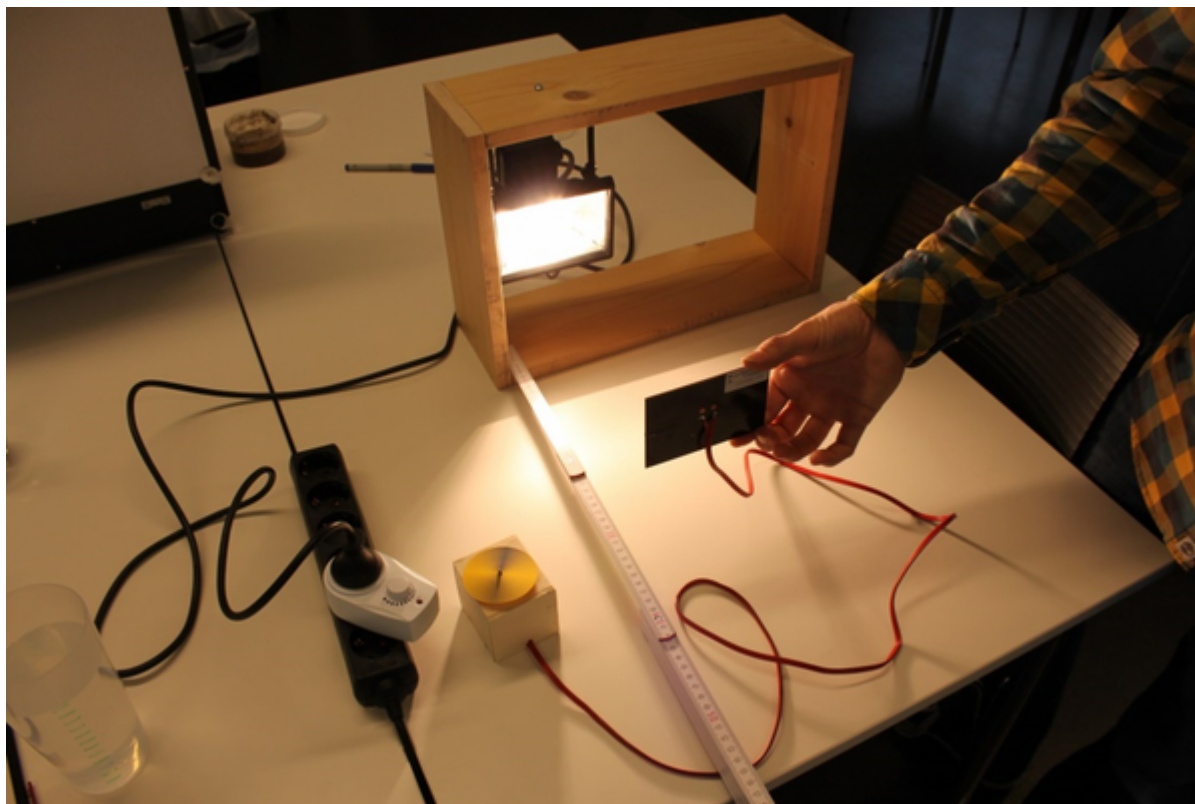
ASTROEDU

Peer-reviewed Astronomy Education Activities

The Engine of Life

What make a planet habitable?

Author: Marco Türk



KEYWORDS

Life, Earth, Thermal radiation, Planets, Black body, Stars, Sun, Exoplanets, Stefan Boltzmann Law, Habitable zone, Extrasolar, ExoMars, Photovoltaic cell, Solar radiation, Orbit, Solar energy



CATEGORY

Planetary systems



LOCATION

Small Indoor Setting (e.g. classroom)



AGE

12 - 16



LEVEL

Middle School



TIME

1h



GROUP

Group



SUPERVISED

No



COST

High Cost



SKILLS

Asking questions, Developing and using models, Planning and carrying out investigations, Analysing and interpreting data, Constructing explanations, Engaging in argument from evidence, Communicating information



TYPE OF LEARNING

Structured-inquiry learning, Discussion Groups, Modelling, Traditional Science Experiment



GOALS

With this model experiment, the students will - understand the qualitative correlation between the distance between a planet and a star and the energy density that affects the planet. - learn that liquid water in a planetary system can only be present in a confined corridor, i.e. the habitable zone. - understand that searching for extra-terrestrial life as we know it means to look for conditions to keep water liquid. - understand that the size and extent of a habitable zone depends on the luminosity of a star.



LEARNING OBJECTIVES

- The students will be able to explain the key conditions needed to find potential life outside Earth.
 - The students will be able to explain the habitable zones of planetary systems and their characteristics.
 - The students will be able to demonstrate how the flux density received by a body depends on its distance from the source.
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BACKGROUND

The Circumstellar Habitable Zone

The most important ingredient to sustain life as we know it is liquid water. Therefore, if scientists want to find planets or other celestial bodies where life may be present, they first want to know if water exists in liquid form there. This, for instance, is also one of the major goals of explorations and investigations of places in the Solar System other than Earth, e.g. Mars.

The presence of liquid water depends on environmental conditions like air temperature and atmospheric pressure. The main driver of the surface temperatures of planets is their distance from the central star they orbit. The temperatures are just right only in a small window so that water does not completely evaporate or freeze. These conditions are modified by local influences like the density of the atmosphere and the composition of potential greenhouse gases. This defines a range around a given star in which liquid water could be present. This range is defined as the 'habitable zone'. If a planet is found orbiting in this zone, it may potentially possess water in the liquid form and thus sustain life as we know it. In the Solar System, Earth occupies the habitable zone. Some models also place Mars in this zone.

There is no guarantee that any planet orbiting within the habitable zone actually possesses notable amounts of liquid water or harbours life, because the conditions on any given planet can be very different. Other boundary conditions that may help to sustain life are energy sources (light, chemical) and magnetic fields to protect from ionising particle radiation.

Did or does Mars support life?

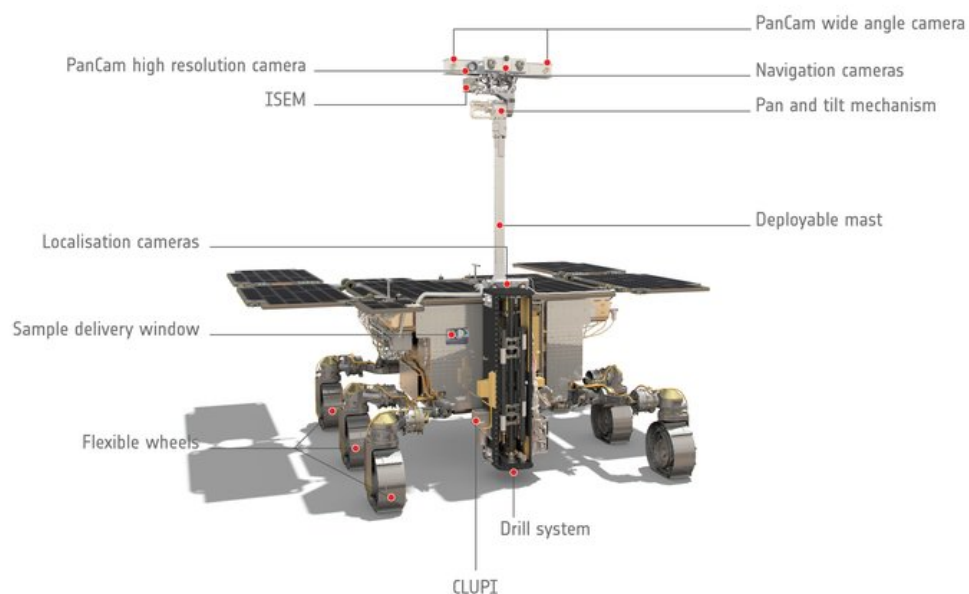
Mars is half the size of the Earth. Its reddish colour is caused by iron oxide (rust), and it has a very thin atmosphere, which mainly consists of carbon dioxide. One of its special features is its many extinct volcanoes, which reach heights of up to 22,000 metres! Like Earth, it also has seasons as its rotation axis is inclined. Theoretically, if the habitable zone of the Solar System is considered, Mars has the potential to be conducive to life.

To date, there is no indication that Mars is or was inhabited. However, there is strong evidence that this planet has harboured liquid water on its surface for a long time. The most common explanation for its current state is that Mars has lost its atmosphere because of which most of the water has either evaporated into space or is still present as ice deposits below the surface. Mars is so small that its gravitational force is rather low; therefore, it can barely hold its atmosphere. In addition, the lack of a magnetic field made it easy for solar wind to deplete the early Martian atmosphere. However, there is some evidence that at least for some time and in a few exceptional regions, there may have been liquid water on its

surface. A high salinity helps keep water liquid even at temperatures below the freezing point of pure water (see Article 1 attached to this activity).

Scientists hope that some form of life could have survived within the ice sheets below the Martian surface. The European Mars programme ExoMars, to be launched in 2020, will investigate this very hypothesis using a robotic laboratory. It will be able to drill below the Martian surface and probe it for chemical and biological activity.

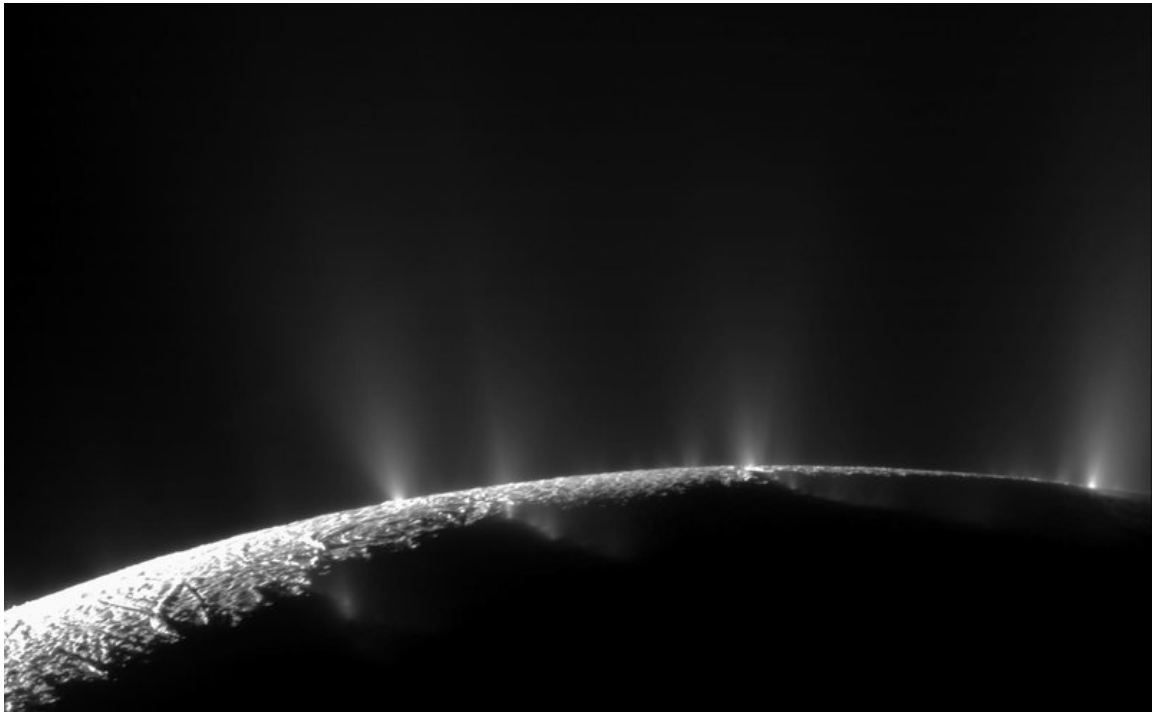
Figure 1: Computer model of the ExoMars rover to be launched in 2020 (ESA/ATG medialab, <http://exploration.esa.int/mars/58885-exomars-rover-front-view-annotated/>, http://www.esa.int/spaceinimages/ESA_Multimedia/Copyright_Notice/Images).



Other locations in the Solar System

During recent years, scientists have entertained the idea that there are other places in the Solar System that might be habitable although they are not within the Sun's habitable zone. In particular, icy moons such as Europa and Enceladus of the gas planets Jupiter and Saturn, respectively, are interesting from this aspect. Observations made during Solar System exploration missions like NASA's Cassini have found evidence of subsurface oceans of liquid water below their thick ice shields (see Article 2 attached to this activity). There is strong evidence that there are hydrothermal vents on the ocean floor of Enceladus (see Article 3 attached to this activity). Similar findings have been made in the terrestrial deep sea on Earth. These vents are colonised with life that feeds on hydrogen released from below.

Figure 2: A dramatic plume sprays water ice and vapour from the south polar region of Saturn's moon Enceladus. Cassini's first hint of this plume came during the spacecraft's first close flyby of the icy moon on 17 February 2005 (NASA/JPL/ Space Science Institute, <https://photojournal.jpl.nasa.gov/catalog/PIA11688>).



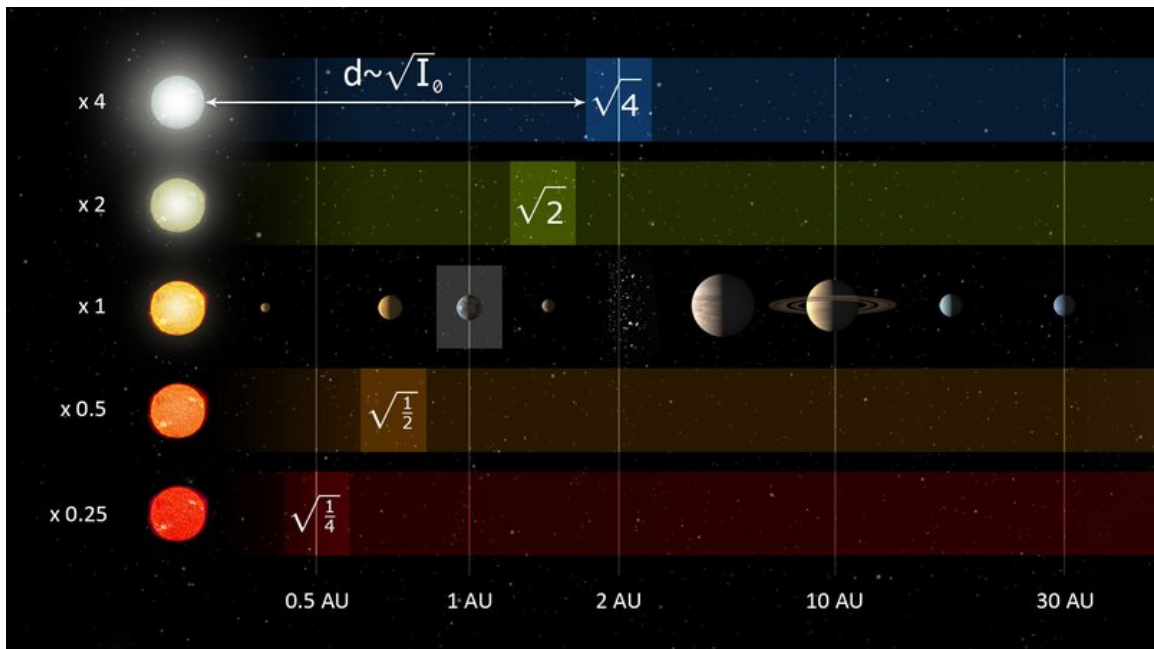
A simple formula for the habitable zone

With the Earth as the template of a habitable planet, one can calculate the distance from any given star where the conditions would be comparable. This distance is proportional to the luminosity of the star.

$$d_{\text{HZ}}(\text{AU}) = \sqrt{\frac{L_{*}}{L_{\odot}}}$$

Here, L_{*} is the luminosity of the star and L_{\odot} is the solar luminosity. The distance d_{HZ} may then represent the location of the habitable zone. Its width depends on what temperatures to expect at the inner and outer edges. There are complex models to predict habitability that even include planetary properties like atmospheric conditions and mass. Therefore, the habitable zone is not really a well-defined range within a planetary system but depends on many properties that allow water to be present in its liquid form.

Figure 3: Distances of habitable zones for stars of varying luminosity (Derpedde, https://de.wikipedia.org/wiki/Datei:Solarsystemau_habit.jpg, 'Solarsystemau habit', <https://creativecommons.org/licenses/by-sa/3.0/legalcode>).



Exoplanets

Planets that orbit stars other than the Sun are called ‘extrasolar planets’ or briefly, ‘exoplanets’. The first exoplanet hosted by a Sun-like star was discovered in 1995 by a Swiss team led by Michel Mayor and Didier Queloz from the University of Geneva. This planet, named 51 Pegasi b, is anything but an Earth-like planet as it revolves around its host star at a distance of only 0.05 AU, i.e. 5% of the mean distance between the Sun and the Earth. Note that even the planet closest to the Sun, Mercury, orbits it at a mean distance of 0.5 AU, i.e. 10 times farther away than 51 Pegasi b is from its host star. In addition, it is a gas giant similar to Jupiter and Saturn. To date (July 2017), we know of 3627 exoplanets, of which 2718 are planetary systems (see <http://www.exoplanets.eu>).

Figure 4: The circumstellar habitable zones of three stars that differ in size, luminosity and surface temperature (NASA/Kepler Mission/D. Berry, <http://aasnova.org/2016/02/24/where-to-look-for-habitability/>).

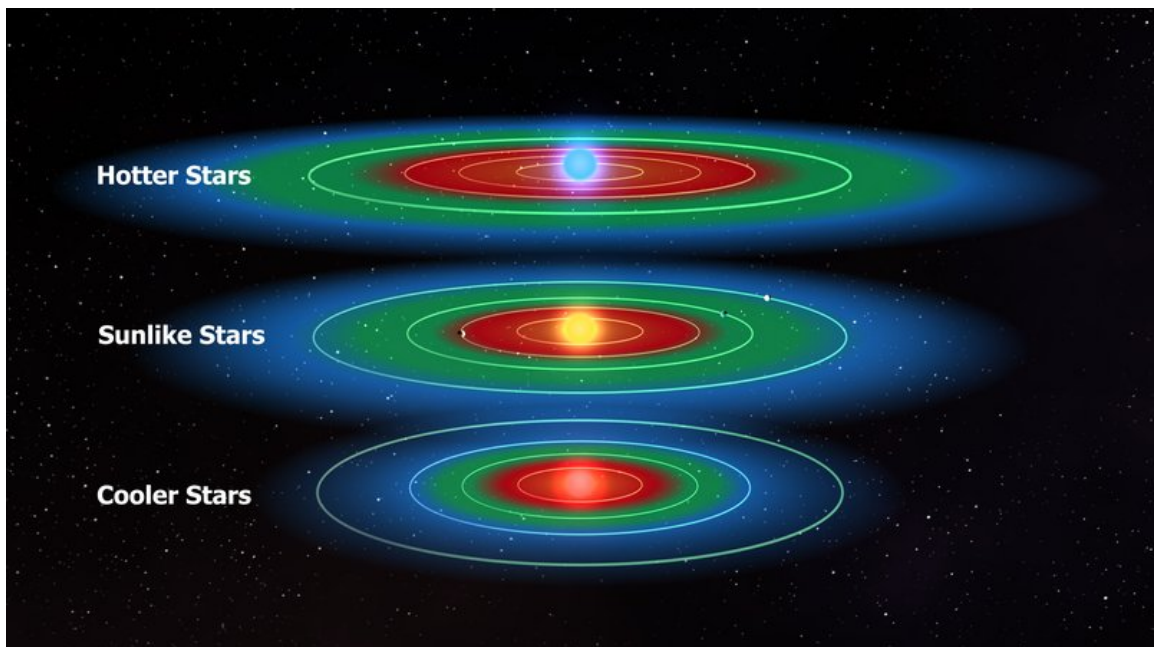


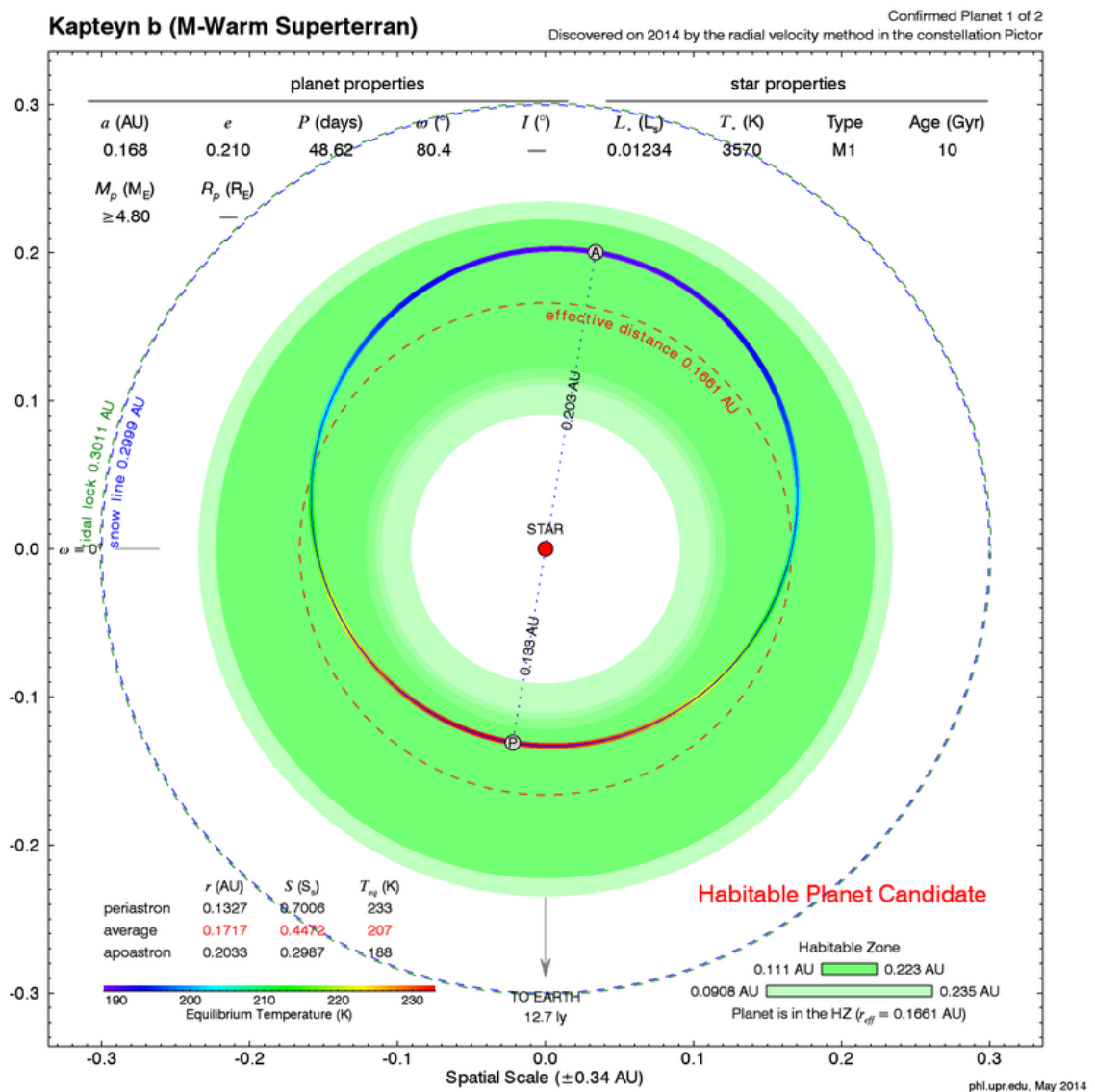
Figure 4 shows the circumstellar habitable zone (in green) for stars of different

temperatures and luminosities. The star in the middle corresponds to stars similar to the Sun. Hotter stars usually have a large and wide habitable zone, while cooler stars can only provide small and narrow habitable zones. In the blue area, it is too cold for liquid water, and in the red area, it is too hot.

Figure 5 shows an example of an exoplanet around the star HD 33793, also known as Kapteyn's star. The star has a surface temperature of about 3570 K. This is about half of the surface temperature of the Sun, which is 5778 K. Thus, the habitable zone (indicated in green) is located at a distance between 0.11 and 0.22 AU.

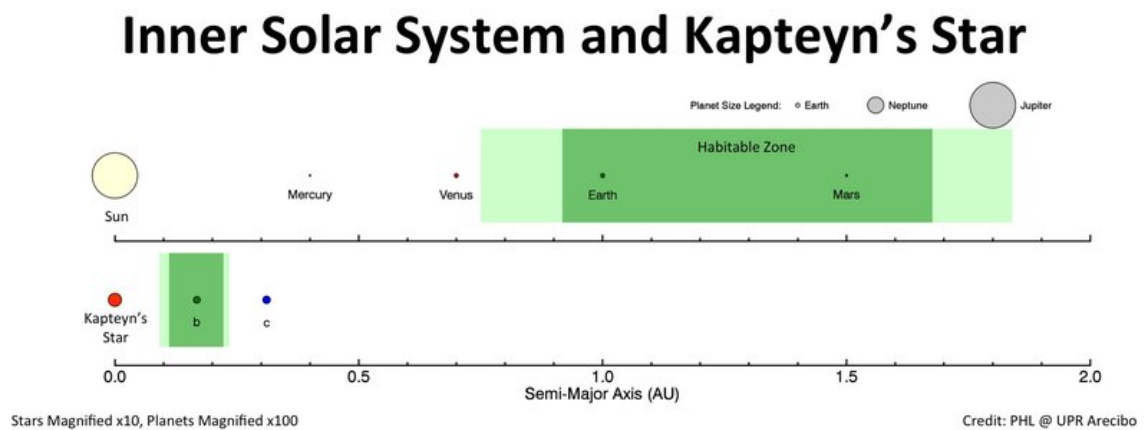
Because of the lower luminosity of this star, the habitable zone is smaller and narrower. When comparing the habitable zones of the Sun and HD 33793 (Figure 6), we find that they considerably differ. The former is both wider and farther away from the Sun.

Figure 5: Habitable zone (green) around the star HD 33793. The orbit of the extrasolar planet Kapteyn b is indicated (PHL/UCP Arecibo, <http://phl.upr.edu/press-releases/kapteyn>, <https://creativecommons.org/licenses/by-nc-sa/3.0/legalcode>, based on: Anglada-Escudé et al. 2014, MNRAS, 443, L89).



The exoplanet Kapteyn b with a mass that is about 5 times that of the Earth is located well within the habitable zone and therefore is interesting for further research on habitability.

Figure 6: Comparison of the habitable zones (green) of the star HD 33793 and the Sun. (PHL/UCP Arecibo, <http://phl.upr.edu/press-releases/kapteyn>, <https://creativecommons.org/licenses/by-nc-sa/3.0/legalcode>, based on: Anglada-Escudé et al. 2014, MNRAS, 443, L89).



FULL DESCRIPTION

INTRODUCTION

A key component of sustaining life on a planet is its ability of carrying liquid water. For this, it is important that the radiation it receives from its central star adequate to keep the temperatures of the planet above a value that permits water to be in the liquid state. Because of this characteristic whereby a potentially habitable planet receives heat from a star at the right distance, this planet can be viewed as an engine of life that needs adequate power to start.

Introduce the topic by asking about the Solar System (planets, composition) and where in this system life evolved. Perhaps, initiate a discussion about the conditions required for planets other than Earth (e.g. Venus, Mars) to sustain life. Try to direct the discussion towards the presence of water.

Question 1: Is there life on Mars?

Expected outcomes from discussion: We haven't found anything that would indicate that there is.

Question 2: Is there liquid water on Mars?

Expected outcomes from discussion: Very little to none. At least not as much that we can expect areas of open water or running rivers.

Question 3: Why are these two things related?

Expected outcomes from discussion: Water is the key to life. Without water, there is no life the way we know it.

Ask the students if they have heard about planets around stars other than the Sun.

Question 4: What does it take to support life on other planets?

Expected outcomes from discussion: There are a few conditions that help in the formation and maintenance of life, but the key is – again – water. Heat is only needed to keep the water liquid, at least in some places. Other conditions that may help are energy sources (light, chemical) or magnetic fields to protect from ionising particle radiation. But since life evolves in oceans, this does not really matter.

Question 5: What conditions are needed to keep water liquid?

Expected outcomes from discussion: Heat and perhaps salt. Salt helps to lower temperatures to keep water liquid.

Question 6: What provides the Earth and other planets with the heat needed to keep water liquid?

Expected outcomes from discussion: Stars, the Sun. The greenhouse effect generated by an atmosphere helps to raise temperatures.

Question 7: What happens to water if it is very cold or very hot?

Expected outcomes from discussion: It freezes or boils and evaporates.

The following experiment is a simple analogy in which the star is represented by a lamp and the planet is represented by a photovoltaic cell combined with a motor.

ACTIVITY 1: ENGINE OF LIFE

Materials needed: - Strong lamp, floodlight - Dimmer switch to regulate the brightness - Folding rule or yardstick - Photovoltaic cell with attached electric motor or fan (ensure that the power the cell generates is adequate to drive the motor)

Figure 7: Illustration showing the soldered connection between a solar cell and a computer fan. Here, the connection can be interrupted with microplugs. The polarity is indicated next to the soldering points of the photovoltaic cell (M. Nielbock).

Experimental set-up 1. Solder the motor to the photovoltaic cell. This is usually very simple. The cells provide soldering points with their polarities indicated. Just use cables (often already attached to the motor) and connect them to the corresponding electrical poles (see Figure 7). 2. A coloured cardboard disc attached to the rotation axis improves the visualisation of the motor's speed as it runs. If a fan is used, the wings may be painted. 3. Plug the lamp into the dimmer and the dimmer into the socket.

Figure 8: Experimental set-up (M. Türk).

Question 8: How will the motor behave if the cell is held at different distances from the lamp?

Expected outcomes from discussion: The rotation speed depends on the distance. Far = slow, near = fast.

Experimental procedure 1. Switch on the lamp. 2. Hold the photovoltaic cell far away from the lamp. The motor should not move. 3. Moving closer to the lamp, determine the distance at which the motor starts moving. 4. Repeat this procedure for different brightness settings of the lamp by using the dimmer.

Tasks:

1. Write down your observations. Describe the results you get when varying the brightness of the lamp.

Expected result: The distance necessary for the electric motor to begin moving is smaller with a dimmed lamp than with a bright lamp.

2. To compare this model experiment with the configuration of the Solar System, life-sustaining conditions (those under which the motor moves) are possible because the Earth (photovoltaic cell) is close enough to the Sun (lamp). The point at which the motor starts running is the outer edge of the habitable zone. What does this experiment tell us about exoplanets in other planetary systems with different stars that are supposed to harbour life?

Expected result: A planet in a planetary system with a star that is less bright than the Sun needs to be located closer to its host star in order to be in the habitable zone.

For ages 14 and higher:

3. What happens to the motor when the cell is very close to the lamp?

Expected result: It runs very fast. It 'overheats'.

4. Can we expect planets sustaining life to be at any distance inside the inner edge of the habitable zone?

Expected result: No, because as the distance decreases, the radiation the planet receives is higher. This leads to increased heating of the planet. If the temperature is too high, water cannot remain liquid.

This activity provides a qualitative impression of the nature and basic principle of the habitable zone. But what does a habitable zone actually look like? The next activity gives an example that is close to scientific research. It shows how one can identify the habitable zone and the planets within it.

ACTIVITY 2: THE HABITABLE ZONE OF KEPLER-62

Materials needed: - Pencils (regular and coloured) - Compass (drawing tool) - Millimetre paper - Ruler - Calculator - Computer with internet access (can be only one operated by the teacher)

Figure 9: Artistic impression of the Kepler-62f exoplanet (NASA Ames/JPL-Caltech).

Kepler-62 is a star that is a little cooler and smaller than the Sun. It is part of the constellation Lyra. In 2014, it was discovered by the Kepler Space Telescope and has five planets orbiting it. The details about Kepler-62 are summarised in Table 1.

Table 1: Properties of Kepler-62.

Property	Value
Name	Kepler-62
Distance	ca. 368 pc
Spectral Type	K2V
Luminosity	0.21 L _☉
Radius	0.64 R _☉
Mass	0.69 M _☉
Surface temperature	4925 K

Figure 10: Comparison between the Solar System and the Kepler-62 planetary system (NASA Ames/JPL-Caltech).

Some of the five exoplanets of Kepler-62 are suspected to be Earth-like. The main properties of the five planets are given in Table 2. All planetary orbits are nearly circular and listed in astronomical units (AU). This is the mean distance between the Sun and Earth.

Table 2: Properties of the five exoplanets of the Kepler-62 system.

Name	Orbital radius (AU)	Mass (Earth masses)	---	---	Kepler-62b	0.0553	ca. 2.1	
Kepler-62c	0.093	ca. 0.1	Kepler-62d	0.120	ca. 5.5	Kepler-62e	0.427	ca. 4.5
Kepler-62f	0.712	ca. 2.8						

Tasks (Drawing a scaled model)

Determine or discuss a suitable scale that allows you to put the entire system on a sheet of paper.

Fill the table (Table 3) with the scaled orbital radii. Round up the values to full millimetres.

The model will show the planetary system from a bird's eye view. Use the compass to draw the scaled circular orbits around the assumed position of the host star Kepler-62.

In the next step, you will add the habitable zone. First, you can apply the simple equation

which only depends on the luminosity of the star. Note that this equation tells you where an Earth-like planet would be located around a Sun-like star of lower luminosity. Use Table 1 to calculate the distance of the habitable zone from Kepler-62. Note that the distance of the habitable zone scales with the square root of the stellar luminosity.

Q: Using this simple relation, where with regard to the Solar System would the habitable zone be if a star had four times the luminosity of the Sun?

A: It would be at twice the distance as compared to the habitable zone of the Solar System.

Calculating the proper boundaries of habitable zones can be tricky and needs sophisticated models. There is an online tool at

<http://depts.washington.edu/naivpl/sites/default/files/hz.shtml>

that performs the calculations when the luminosity and surface temperature of the star are provided (This can be done by the teacher instead of providing computer access for all students.). All you have to do is enter the surface temperature T_{eff} and the luminosity of the star in the upper two fields, as shown in Figure 11. Note that after entering a value, you have to click in the field again.

Figure 11: Screen shot of the online tool to calculate the dimensions of a habitable zone. The example above shows the values of the Sun. Important: After inserting the values, you have to click in the field to submit the entry (<http://depts.washington.edu/naivpl/sites/default/files/hz.shtml>).

Use the values of Kepler-62 from Table 1. Use the result labelled as 'Conservative habitable zone limits (1 Earth mass)' and 'HZ distance from the star (AU)'. Add the distances for the inner and outer edges of the habitable zone to the table below and calculate the scaled radii.

Table 3: Orbital parameters of the Kepler-62 planetary system (The scaled values are optimised for a sheet of A4 paper with a width of 18 cm. They are not provided with the worksheets).

Name	Orbital radius (AU)	Scaled radius (cm)	---	---	Kepler-62b	0.0553	0.60	
Kepler-62c	0.093	1.01	Kepler-62d	0.120	1.30	Kepler-62e	0.427	4.64
Kepler-62f	0.712	7.74	Habitable Zone (inner)	0.456	4.96	Habitable Zone (outer)	0.828	9.00

Q: How well does the simple distance of the habitable zone agree with the model calculation?

A: The simple value is close to the inner edge of the more accurately calculated habitable zone.

Q: Can you think of a reason why the simple solution is so close to the extreme value of the modelled solution? In which way do the two approaches differ? (Hint: If the students have difficulties with the answer, let them use the online calculator with the solar surface temperature instead of the stellar luminosity.)

A: The simple approach does not take into account the surface temperature.

Q (perhaps better suited for higher term classes): How does the missing parameter (surface temperature) influence the radiation characteristics of Kepler-62?

A: Lower temperatures mean redder spectra. The spectrum of Kepler-62 contains a relatively higher amount of infrared radiation than that of the Sun. This is more effective in directly heating planetary atmospheres.

Now add the inner and outer edges of the habitable zone to the scaled model of the planetary system.

You can colour the area between the inner and outer edges of the habitable zone. Green would be appropriate.

Figure 12: Model of the Kepler-62 system (solution not presented to the students).

Q: Which of the planets are inside the habitable zone?

A: Kepler-62f



EVALUATION

The students should be able to explain, in their own words, the phenomenon observed.

They should also be able to record and analyse data on their own and draw the necessary conclusions.

With support, they should be able to explain their observations correctly. In cases in which the necessary physical concepts have not been reviewed yet, the students should be able to explain their observations in their own words.

Ask the students if there is life on Mars and if there is water on Mars. Ask the students if there is any relationship between them. Ask them what it takes to support life on other planets. The replies should indicate that water is the most important requirement for life as we know it to be sustained.

Ask the students what conditions are needed to keep water liquid (temperature). Ask them what provides us and other planets with the heat to keep water liquid (the Sun). Where in the Solar System are the hottest/coldest planets and why (the temperature decreases as the distance from the Sun increases)? As an analogue, tell the students to imagine holding a hand above a stove. Ask them how the sensation of heat changes when the hand is held at different heights from the stove.

When reviewing the hands-on experiment with the lamp and solar cell, tell the students that the voltage the cell provides depends on the received radiation. Ideally, the total power emitted by the lamp remains the same for any point in time. Therefore, for any given distance, the power summed up at all points around the lamp is constant. Ask the students to imagine placing a number of solar cells around the lamp that would be able to receive the total power. Would they need more, less or the same number of cells when trying to do this at a larger distance? What are the implications for the portion of radiation received by a single cell? This picture should be able to convince the students that the power per solar cell (a fixed area) is reduced when it is placed at a larger distance.



CURRICULUM



ADDITIONAL INFORMATION

This activity is part of a larger toolbox called the 'Climate Box', which was developed within the space education project 'EU Space Awareness', funded by the European Commission.



CONCLUSION

This activity teaches the students about the habitable zones of planetary systems. It comprises a simple experiment that demonstrates how the amount of radiation received by a body depends on its distance from the source. The experiment consists of a strong lamp and a photovoltaic cell that receives its power from the lamp and drives a motor as soon as the power is sufficiently high. This is relevant for understanding the dimensions of a habitable zone where liquid water can be present in certain boundary conditions. The running motor depicts the running engine of life within a planetary system. In addition, students can understand the composition of a real exoplanetary system and its habitable zone in the second activity, by calculating and drawing a scaled model of it.

CITATION

Marco Türk, , *The Engine of Life* , [astroEDU, 1624](https://astroEDU,1624) doi:10.14586/astroedu/1624

ACKNOWLEDGEMENT

Haus der Astronomie, Markus Nielbock; Leiden Observatory, Jorge Rivero Gonzalez
