Super-Earths and searching life beyond our Solar System

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Exoplanets

Exoplanet, extrasolar planet - a planet that orbit a star (or stars) other than the Sun.

1. The first exoplanet was discovered in 1992.
2. Nowadays (the first half of 2020) there are over 4000 confirmed exoplanets.
3. The most discovered exoplanets moves in a distance smaller than 1000 ly[1]
4. Some exoplanets may be potential life-bearing worlds.
5. The most exoplanets have been discovered by indirect techniques of detection.

Figure: Exoplanet in a three-star world (the artist's conception). Source: http://www.boulder.swri.edu/~terrell/dtart.htm

[1] The light-year (ly) is a unit of length that measures about 9.46 trillion kilometers. A light-year is the distance that light travels in vacuum in one Julian year (365.25 days) from the Sun.

Super-Earths

Super-Earths are bigger than Earth-like exoplanets but less massive than Uranus and Neptune (from 1.25 to 4 Earth-mass).[2]

1. The first Super-Earths were discovered in 1992 by polish astronomer Aleksander Wolszczan.
2. Orbital period of the most known Super-Earth is smaller than 100 days.
3. The most common value of radius of their orbit is of order 0.05 au[3].
4. Nowadays (the first half of 2020) there are over 1000 confirmed Super-Earths.

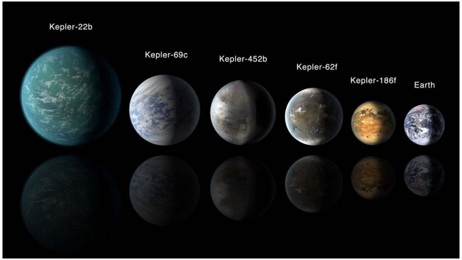


Figure: Artist's impression of a few known Super-Earths. Source: https://exoplanets.nasa.gov

[2] Definitions may vary, some people define a super-Earth as a exoplanet with a mass between 1 and 10 times that of Earth.

[3] The astronomical unit (au) is the average distance between Earth and the Sun and is equal to about 150 million kilometres.

Methods of detecting exoplanets: Doppler spectroscopy (also known as the radial-velocity method)

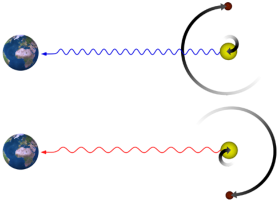


Figure: In the Doppler spectroscopy method periodic shifts in radial velocity of the host star are detected. A star and a planet move around their centre of mass (see the supplementary material to learn more about it). If the star moves towards the Earth light waves leaving the star are shifted towards the blue end of the spectrum. Conversely, if the star moves away from the Earth light waves leaving the star are shifted towards the red end of the spectrum. This change of wavelength is caused by the presence of planets, which exert a gravitational influence on their respective star. Source: https://phys.org

Link:
https://www.youtube.comwatch?v=WK0WAmiP_D

Methods of detecting exoplanets: transit method

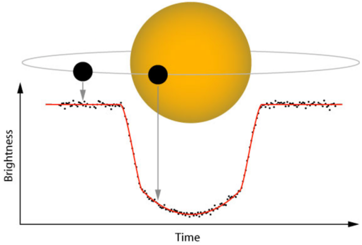
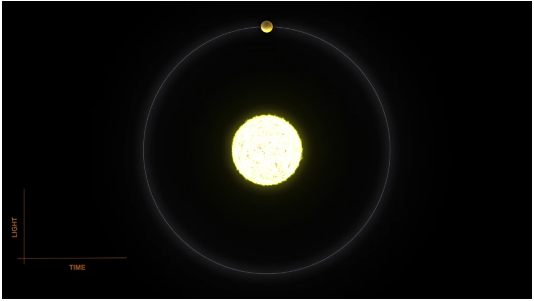


Figure: The transit occurs when the planet passes in front of its star and dim some of its light.This method only works for planets that have orbits aligned in such a way that, as seen from the Earth, the planet passes in front of its star. Source: https://heasarc.gsfc.nasa.gov/docs/tess/primary-science.html



Link: https://www.youtube.comwatch?v=OFdZv2GP4gM

Methods of detecting exoplanets: astrometry method

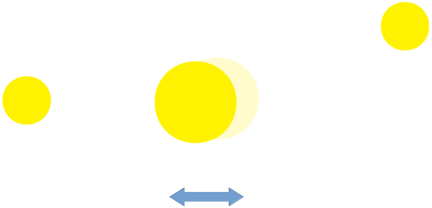
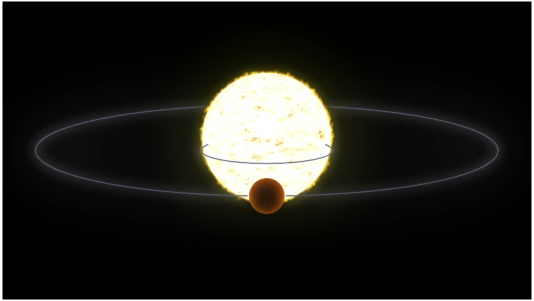


Figure: In astrometry method the motion of a star is detected by making precise measurements of its position on the sky. This motion may suggests that the star is surrounded by a planet. Source: self-produced.



Link: https://www.youtube.comwatch?v=l46-8PvT44Y

Methods of detecting exoplanets: gravity microlensing method

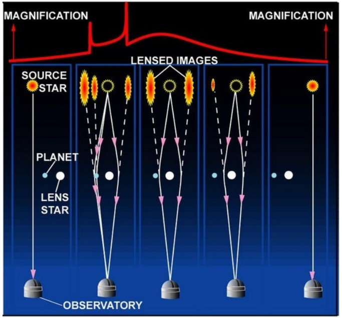
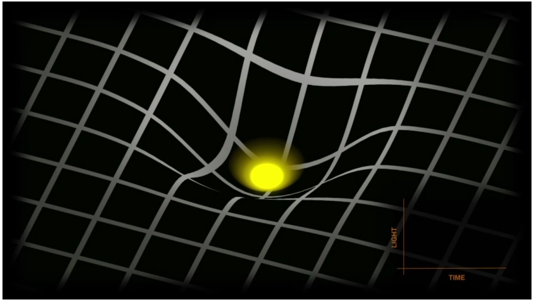


Figure: When a star (white) passes in front of another star (yellow), it bends the distant starlight like a lens, making it brighter. If the lensing star has an exoplanet, this planet adds its own lensing effect and create the two characteristic spikes in the light curve. Source: http://www.planetary.org/explore/space-topics/exoplanets/microlensing.html



Link:
https://www.youtube.comwatch?v=dZEUOoe2c2I

Methods of detecting exoplanets: direct detection and imaging method

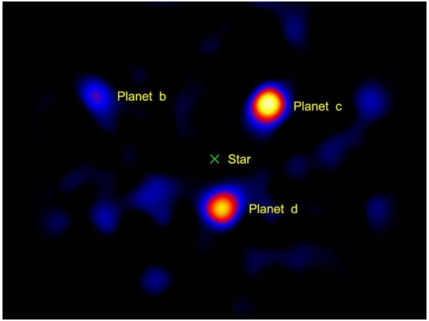
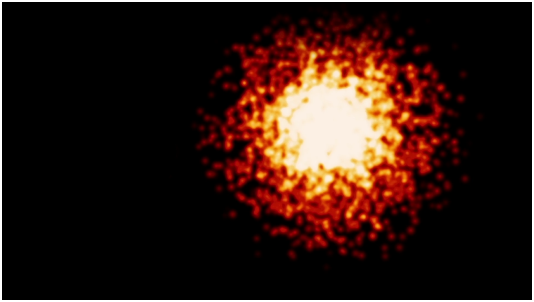


Figure: Direct image of exoplanets around the star HR8799.[5] Source: https://www.nasa.gov/topics/universe/features/exoplanet20100414-a.html



Link: https://exoplanets.nasa.govalien-worldsways-to-find-a-planet#3

[5] The designation HR 8799 is the star's identifier in the Bright Star Catalogue. This star is in 8799 position on this catalogue.

Some exoplanetary statistics

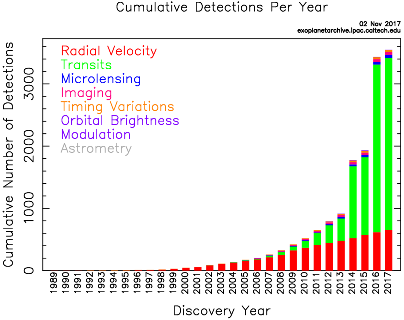


Figure: Cumulative detections of exoplanets per year as of 2017, color coded by method. Source: https://exoplanetarchive.ipac.caltech.edu

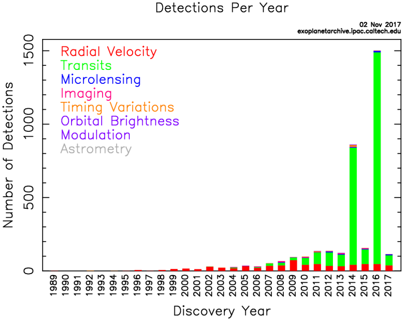


Figure: Exoplanet detections by year as of 2017, color coded by method. Source: https://exoplanetarchive.ipac.caltech.edu

Favorable conditions to the emergence of life

Favorable conditions on exoplanets to the emergence of life:

1. The object's surface temperature comes within eg. -70° and 80°.
2. The object has a dense atmosphere with biosignatures[6] in it (O_2, O_3, CH_4, liquid H_2O).
3. There are liquid water reservoirs underneath the object's surface.
4. There is a specific collection of isotopes of different elements such as C, H, N, which couldn't be created without living organisms' contribution.

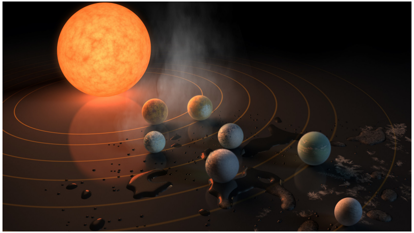


Figure: Artist's impression of TRAPPIST-1 planetary system[7]. Source: https://exoplanets.nasa.gov

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[6] A chemical or physical marker indicating the presence of life, especially something sought in geologic formations or in an extraterrestrial environment. Definition taken from https://www.thefreedictionary.com

[7] Planets around the star TRAPPIST-1 were first detected by the TRAPPIST (TRAnsiting Planets and PlanetesImals Small Telescope) telescope at ESO's La Silla Observatory in 2016. They are named TRAPPIST-1b,c,d,e,f,g and h, with increasing distance from the star.

The search of life on exoplanets

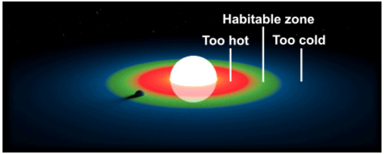
1. Searching for radio signals to receive.
2. Contents of exoplanets' atmospheres (looking for biosignatures).
3. The size and density of exoplanet (based on it we can judge if it's made of rocks or gasses, or does it e.g. contain water).
4. The angle between an exoplanet's rotational axis and its orbital axis, length of day.
5. Picking exoplanets with conditions suitable to sustain life (those in the habitable zone).

Figure: Artist's impression of the surface of a planet in a double system. Source: https://exoplanets.nasa.gov

The search for exoplanets in habitable zones

Habitable zone (also known as ecosphere or Goldilocks zone) is an area in a spherical shape located around a star where physical and chemical conditions necessary to sustain life can be present (especially liquid water and temperatures ranging, for instance, from -70°C to +80 °C).

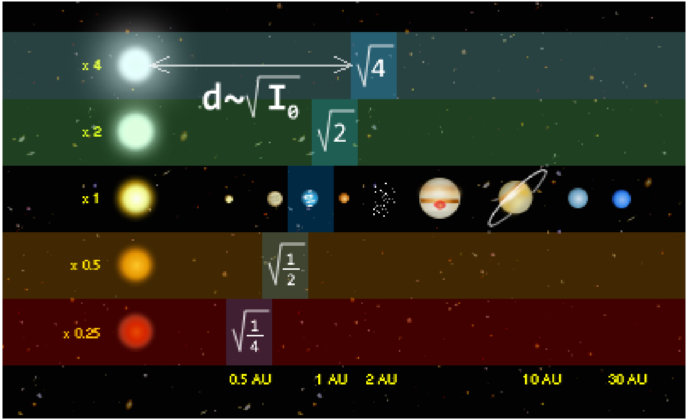
1. In the Solar System it is in the distance from 0,72 to 1,52 au from the Sun (definitions may vary).
2. The location of the habitable zone depends on the star's parameters, e.g. its brightness.
3. The location of the habitable zone depends on many factors such as composition of the atmosphere (clouds, glasshouse gasses, etc.) or planet's albedo.
4. Liquid water can exist on an exoplanet (exomoon) due to the heat caused by existence of tidal forces.
5. Habitable zones of exoplanets where life is e.g. ammonia based can be located in completely different places (other temperature of ammonia's melting).



Source: http://earth-chronicles.com/space/the-habitable-zone.html

The search for exoplanets in habitable zones

Because in most cases we don't know an exoplanet atmosphere's composition and its other parameters we can assume (in a certain approximation), that an exoplanet's position is determined by formula $d \sim \sqrt{I}$, where d is the distance from a star, I is the star's luminosity and $\sim$ means "is proportional to".[8]



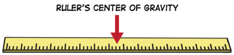
Source: public domain.

[8]The relationships between the star's luminosity, its radius, brightness and temperature are described in the additional material at the end of this presentation. Two experiments on these topics are also proposed.

Additional material

Centre of mass of two orbiting objects

1. We say that the planets revolve around the stars, which is not true. Planets and stars actually orbit around a common center of mass known as the barycenter.
2. Every object has a centre of mass, is the point at which it can be balanced.



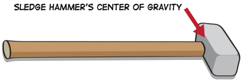


Figure: The centre of mass of a ruler is the centre of the object, but in case of hammer, it has most of the mass on one end, so its center of mass is much closer its heavy end. Credit: https://spaceplace.nasa.gov/barycenter/en/

3. In space, two bodies orbiting each other, for example a star and a planet, also have a mass centre.

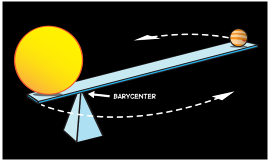


Figure: In space, barycentre of objects is the point around which the objects orbit. Credit: https://spaceplace.nasa.gov/barycenter/en/

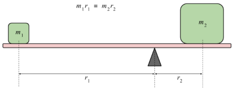
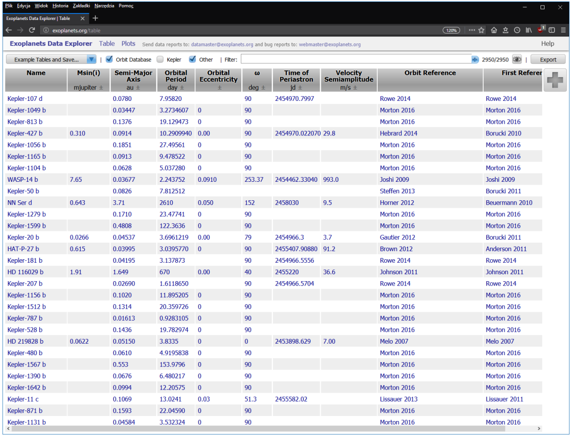


Figure: The barycenter of two objects is the point for which $r_1 m_1 = r_2 m_2$. Exercise: find a barycenter between Earth and the Sun and Jupiter and the Sun. Credit: https://medium.com/@cosinekitty/our-wobbly-solar-system-8d4014040e42

Exoplanet catalogue

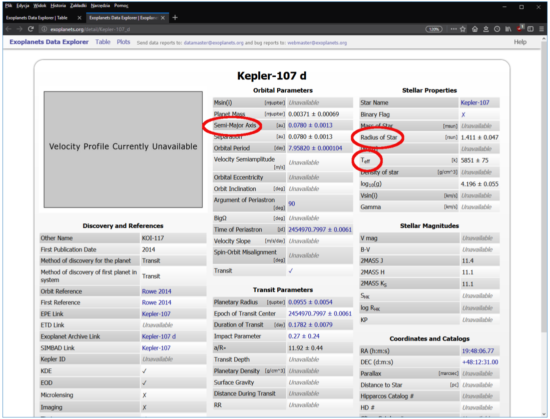
Link to the catalogue: `http://exoplanets.org/table`. After clicking on the preceding link the following view appears, where an exoplanet's name is given in the first column. By clicking on the "**Name**" button we can sort the exoplanets by their names. The "**Filter**" field allows us to filter exoplanets by their names.



Name	Msin(i) mjupiter ±	Semi-Major Axis au ±	Orbital Period day ±	Orbital Eccentricity ±	ω deg ±	Time of Periastron jd ±	Velocity Semiamplitude m/s ±	Orbit Reference	First Referer
Kepler-107 d		0.0780	7.95820		90	2454970.7997		Rowe 2014	Rowe 2014
Kepler-1049 b		0.03447	3.2734607	0	90			Morton 2016	Morton 2016
Kepler-813 b		0.1376	19.129473	0	90			Morton 2016	Morton 2016
Kepler-427 b	0.310	0.0914	10.2909940	0.00	90	2454970.022070	29.8	Hebrard 2014	Borucki 2010
Kepler-1056 b		0.1851	27.49561	0	90			Morton 2016	Morton 2016
Kepler-1165 b		0.0913	9.478522	0	90			Morton 2016	Morton 2016
Kepler-1104 b		0.0628	5.037280	0	90			Morton 2016	Morton 2016
WASP-14 b	7.65	0.03677	2.243752	0.0910	253.37	2454462.33040	993.0	Joshi 2009	Joshi 2009
Kepler-50 b		0.0826	7.812512					Steffen 2013	Borucki 2011
NN Ser d	0.643	3.71	2610	0.050	152	2458030	9.5	Horner 2012	Beuermann 2010
Kepler-1279 b		0.1710	23.47741	0	90			Morton 2016	Morton 2016
Kepler-1599 b		0.4808	122.3636	0	90			Morton 2016	Morton 2016
Kepler-20 b	0.0266	0.04537	3.6961219	0.00	79	2454966.3	3.7	Gautier 2012	Borucki 2011
HAT-P-27 b	0.615	0.03995	3.0395770	0	90	2455407.90880	91.2	Brown 2012	Anderson 2011
Kepler-181 b		0.04195	3.137873		90	2454966.5556		Rowe 2014	Rowe 2014
HD 116029 b	1.91	1.649	670	0.00	40	2455220	36.6	Johnson 2011	Johnson 2011
Kepler-207 b		0.02690	1.6118650		90	2454966.5704		Rowe 2014	Rowe 2014
Kepler-1156 b		0.1020	11.895205	0	90			Morton 2016	Morton 2016
Kepler-1512 b		0.1314	20.359726	0	90			Morton 2016	Morton 2016
Kepler-787 b		0.01613	0.9283105	0	90			Morton 2016	Morton 2016
Kepler-528 b		0.1436	19.782974	0	90			Morton 2016	Morton 2016
HD 219828 b	0.0622	0.05150	3.8335	0	0	2453898.629	7.00	Melo 2007	Melo 2007
Kepler-480 b		0.0610	4.9195838	0	90			Morton 2016	Morton 2016
Kepler-1567 b		0.553	153.9796	0	90			Morton 2016	Morton 2016
Kepler-1390 b		0.0676	6.480217	0	90			Morton 2016	Morton 2016
Kepler-1642 b		0.0994	12.20575	0	90			Morton 2016	Morton 2016
Kepler-11 c		0.1069	13.0241	0.03	51.3	2455582.02		Lissauer 2013	Lissauer 2011
Kepler-871 b		0.1593	22.04590	0	90			Morton 2016	Morton 2016
Kepler-1131 b		0.04584	3.532324	0	90			Morton 2016	Morton 2016

Parameters of exoplanets and stars necessary to find the size of a habitable zone

By clicking on an exoplanet's name (left column) we get to see the following view, where red ellipses mark placements of parameters needed to determine the size of a habitable zone and whether or not the planet is inside it.



Red ellipses mark correspondingly:

1. Exoplanet's semi-major axis a expressed in au[9].
2. Radius of a star, $R_{\odot}$, expressed as a multiple of the Sun's radius.
3. Star's effective temperature, T^*_{eff}, expressed in Kelvins.

[8] It is the average distance of an exoplanet from its star.

Size of habitable zone

The minimal limit of the habitable zone around a star:

$$r_{min} = r_0 \frac{R_\star}{R_\odot} \left(\frac{T_{eff}^\star}{T_{eff}^\odot} \right)^2 \quad (1)$$

The maximal limit of the habitable zone around a star:

$$r_{max} = r_1 \frac{R_\star}{R_\odot} \left(\frac{T_{eff}^\star}{T_{eff}^\odot} \right)^2 \quad (2)$$

where R_* and $R_\odot$ are respectively the radius of a star around which an exoplanet revolves and of the Sun (we assume that the radius of the Sun equals 1), and T_{eff}^* and $T_{eff}^\odot$ are respectively the effective temperature[10] of a star and the Sun. For the Sun we should assume $T_{eff}^\odot = 5772$ K. We assume that an exoplanet is inside the habitable zone if $r_{min} \leq a \leq r_{max}$ is true, where a is the average distance between an exoplanet and its star (the semi-major axis). r_0=0.72 au (the average distance of Venus from the Sun), r_1=1.52 au (the average distance of Mars from the Sun).

[10] Effective temperature of a star is the temperature that an black body has to have in order to emit the same amount of energy as this star.

Example of an analysis

Planet Kepler 107-d revolving around the Kepler 107 star[11]

For this object we have $a = 0.078$ au; for its star $T^*_{eff} = 5851\text{K}$ and its radius $R_* = 1.411 R_\odot$. We leave out measurement uncertainties for the sake of these calculations. From the first formula we know the minimal limit of the habitable zone:

$$r_{min} = 0.72 \text{ au} \frac{1.411 R_\odot}{1 R_\odot} \left(\frac{5851\text{K}}{5772\text{K}} \right)^2 = 1.04 \text{ au} \tag{3}$$

and from the second one the maximal limit:

$$r_{max} = 1.52 \text{ au} \frac{1.411 R_\odot}{1 R_\odot} \left(\frac{5851\text{K}}{5772\text{K}} \right)^2 = 2.20 \text{ au} \tag{4}$$

Thus we concluded that the habitable zone around Kepler 107 star is between 1.04 au and 2.22 au away from its centre. Planet Kepler 107-d is at the average distance of 0.078 au from the star, which means it is way closer to it than the habitable zone.

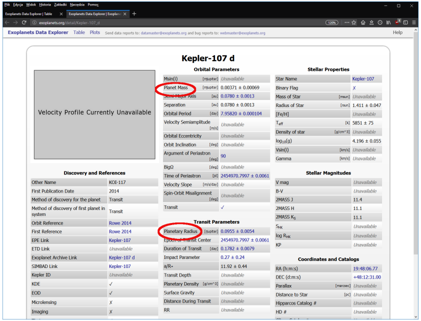
[11] Names of this exoplanet and the star come from NASA's space telescope Kepler looking for terrestrial extrasolar planets. We know 4 planets revolving around the star Kepler 107, they are called Kepler 107-b, Kepler 107-c, Kepler 107-d and Kepler 107-e. All planets discovered by Kepler telescope are named analogically, starting with the letter b.

Materials for the extended version of the lesson

Having exoplanets inside habitable zones we can now focus to finding those Earth-like (terrestrial) ones, assuming the following limitations for chosen exoplanets:

1. More restrictive limitations: $0.5R_\oplus < R_p \leq 1.5R_\oplus$ and\or $0.1m_\oplus < m_p \leq 5m_\oplus$
2. Less restrictive limitations: $0.5R_\oplus < R_p \leq 2.5R_\oplus$ and\or $0.1m_\oplus < m_p \leq 10m_\oplus$

Where R_p and $R_\oplus$ are respectively radius of the planet and of the Earth, m_p and $m_\oplus$ are respectively mass of the planet and of the Earth. However, it's worth noting that for not all planets this data is available.



exoplanets.org/detail/Kepler-107_d

Exoplanets Data Explorer | Table | Plots | Send data reports to: datamaster@exoplanets.org and bug reports to: webmaster@exoplanets.org | Help

Kepler-107 d

Velocity Profile Currently Unavailable

Discovery and References

Other Name	KOI-117
First Publication Date	2014
Method of discovery for the planet	Transit
Method of discovery of first planet in system	Transit
Orbit Reference	Rowe 2014
First Reference	Rowe 2014
EPE Link	Kepler-107
ETD Link	Unavailable
Exoplanet Archive Link	Kepler-107 d
SIMBAD Link	Kepler-107
Kepler ID	Unavailable
KDE	✓
EOD	✓
Microlensing	✗
Imaging	✗

Orbital Parameters

Msin(i) [mjupiter]	Unavailable
Planet Mass [mjupiter]	0.00371 ± 0.00069
Semi-Major Axis [au]	0.0780 ± 0.0013
Separation [au]	0.0780 ± 0.0013
Orbital Period [day]	7.95820 ± 0.000104
Velocity Semiamplitude [m/s]	Unavailable
Orbital Eccentricity	Unavailable
Orbit Inclination [deg]	Unavailable
Argument of Periastron [deg]	90
BigΩ [deg]	Unavailable
Time of Periastron [jd]	2454970.7997 ± 0.0061
Velocity Slope [m/s/day]	Unavailable
Spin-Orbit Misalignment [deg]	Unavailable
Transit	✓

Transit Parameters

Planetary Radius [rjupiter]	0.0955 ± 0.0054
Epoch of Transit Center	2454970.7997 ± 0.0061
Duration of Transit [day]	0.1782 ± 0.0079
Impact Parameter	0.27 ± 0.24
a/R*	11.92 ± 0.44
Transit Depth	Unavailable
Planetary Density [g/cm^3]	Unavailable
Surface Gravity	Unavailable
Distance During Transit	Unavailable
RR	Unavailable

Stellar Properties

Star Name	Kepler-107
Binary Flag	✗
Mass of Star [msun]	Unavailable
Radius of Star [rsun]	1.411 ± 0.047
[Fe/H]	Unavailable
T_{eff} [k]	5851 ± 75
Density of star [g/cm^3]	Unavailable
$log_{10}(g)$	4.196 ± 0.055
Vsin(i) [km/s]	Unavailable
Gamma [km/s]	Unavailable

Stellar Magnitudes

V mag	Unavailable
B-V	Unavailable
2MASS J	11.4
2MASS H	11.1
2MASS K_S	11.1
S_{HK}	Unavailable
log R_{HK}	Unavailable
KP	Unavailable

Coordinates and Catalogs

RA (h:m:s)	19:48:06.77
DEC (d:m:s)	+48:12:31.00
Parallax [marcsec]	Unavailable
Distance to Star [pc]	Unavailable
Hipparcos Catalog #	Unavailable
HD #	Unavailable

Red ellipses mark respectively:

1. Planet mass, m_p, expressed as a multiple of Jupiter's mass.
2. Planetary radius, R_p, expressed as a multiple of Jupiter's mass.

In the calculations we have to assume Jupiter's mass as 317.83 masses of Earth, however Jupiter's radius as 10.517 times Earth's radius.

Materials for the experimental part of the lesson: brightness and luminosity of a star (optional)

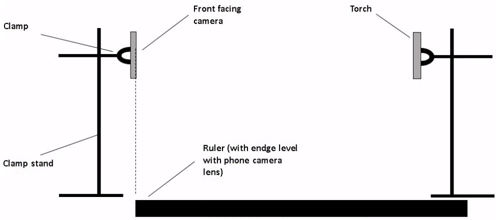
The brighness of a star is determined by two factors:

1. Luminosity - how much energy the star puts out in a given unit of time.
2. Distance - how far the star is from us.

Connection between these quantities is given by the inverse square law. This law states that:

$$\text{Brightness} \sim \frac{1}{(\text{distance})^2} \tag{5}$$

In this experiment, you will use an android mobile with the lux app installed and a second mobile phone with a torch function.[12]



[12] See the document Description.docx for details.

Materials for the experimental part of the lesson: brightness and luminosity of a star (optional)

The brighness of a star is determined by two factors:

1. Luminosity - how much energy the star puts out in a given unit of time.
2. Distance - how far the star is from us.

Connection between these quantities is given by the inverse square law. This law states that:

$$\text{Brightness} \sim \frac{1}{(\text{distance})^2} \tag{6}$$

The inverse square law can also be easily demonstrated by using a light bulb and a shadow (for example a piece of cardboard with a hole). A certain amount of light passes through the hole at a distance of 1 m from the light source. At distances of 2 m and 3 m from the source, the same amount of light spreads out to cover 4 and 9 times the hole's area, respectively.

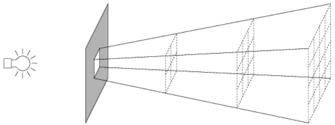


Figure: If the distance between the light source and the surface is doubled, the light source illuminates a surface area four times bigger than the one before. It implies that the light brightness decreases to a quarter. Source: https://www.ifa.hawaii.edu/~barnes/ASTR110L_S03/inversesquare.html

Materials for the experimental part of the lesson: radius and temperature of a star - part I (optional)

Luminosity of a star is also related to its size. The larger the star is, the more energy it emits and the brighter it is. It is also related to the temperature of the star. The relation is:[13]

$$\text{Luminosity} \sim (\text{radius})^2 \times (\text{temperature})^4 \tag{7}$$

When matter is hot enough, it emits visible light. When heated to the same temperature, bulbs filaments, metals, many others materials and stars will emit the same characteristic blend of color of light.[14] The stars are different colours: red, orange, yellow white and blue. The colour of stars provides information about the surface temperature of the star. The coldest stars are red and the hottes are blue.

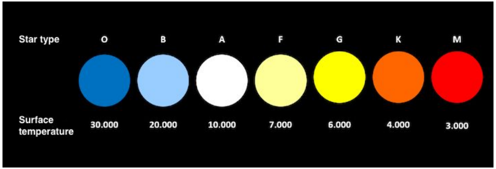


Figure: Star colour and temperature (in Kelvins). Source:
https://www.bbvaopenmind.com/en/science/physics/the-colour-of-stars-treasure-map-for-astronomers

[13] This relation is the Stefan-Boltzmann law written in a different form.

[14] The light emitted by a light source does not always indicate its temperature. Examples are the LED or fluorescent lamps.

Materials for the experimental part of the lesson: radius and temperature of a star - part II (optional)

The colour temperature can be simply demonstrated in the following experiment using a light bulb (for example a 6V bulb) and a variable DC energy supply. The experimental set-up is simple: the bulb is connected to the variable DC energy supply. Next gradually increase the voltage, observe the colour and intensity of the light emitted by the bulb's filament. The temperature of the filament can be approximated by comparing its color with those in the figure below.

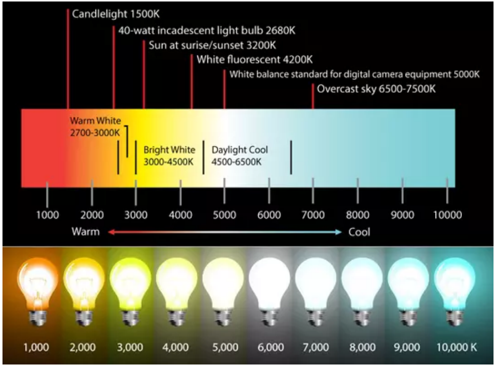


Figure: Colour temperature scale for light bulbs. Source: https://m.kaskus.co.id/thread/5945c2e0c2cb17a2628b456b