DEPARTMENT OF PHYSICS
AND ASTRONOMY
*Faculty of Science
and Engineering*

MACQUARIE
University

The Hunt for New Worlds

Figure 1: Illustration of an exoplanetary system (Credit: Credit: NASA/JPL-Caltech)

Introduction

The planets of our Solar System typically fall into two distinct categories.

1. The terrestrial planets, Mercury, Venus, Earth and Mars, are characterised by their relatively small size, high density and small number of satellites.

2. The gas giants, Jupiter, Saturn, Uranus and Neptune exhibit almost opposite characteristics: large diameters, low densities and numerous satellites and ring systems.

Thanks to advanced telescope construction and instrumental resolution, we can now observe these planets and satellites from Earth with great detail. Numerous spacecraft have also been launched in the interest of planetary science. We've landed rovers and probes on Earth's Moon, Venus, Mars and Saturn's Titan, dropped probes into Jupiter's atmosphere and conducted flybys of all major planets, numerous comets and asteroids. As a result, we now have a good understanding of the formation and evolution of our Solar System, but we still lack the complete picture as well as the big questions: Is Earth unique in the Universe? Do other planets and moons harbour life? Intelligent life? To help answer these, we decided to step out of our backyard and take aim at the rest of the Galaxy.

The study and characterisation of extra-solar planets (aka exoplanets) represents one of the most dynamic and exciting new research fields in astrophysics. Our knowledge in the area has grown exponentially thanks to our understanding of their formation and evolution to the development of various methods to detect them. Facilitating this growing knowledge are three main areas of research:

- The analysis of the planetary populations in our Galaxy
- The understanding of formation and evolution of planetary systems
- The search for biological markers in exoplanets, which contributes to the 'ultimate' goal, the search for extra-terrestrial intelligent life

One of the most practical ways to hunt for exoplanets is to watch for the periodic dimming of a star caused by a planet passing in front of it—an event known as a transit. Measurements of this change in brightness are known as photometry. Observations of exoplanet transits provide a significant amount of information. Analysis of light curves can help determine the relative dimensions of the exoplanet and its host star, clues about the temperature and composition of the planetary atmosphere, and when coupled with other detection methods, we can even work out its mass, density and composition.

The aim of this exercise is for you to create a light curve from an exoplanet transit by conducting photometry measurements on sample data from the Las Cumbres Observatory Global Telescope Network. Sample data is provided by way of 10 FITS images and 1 reference image. These should be in a folder on your desktop.

Instructions

1. Open the software, *AstroImageJ*.
2. Click on `File > Import > Image Sequence` and select one of the FITS files and click on `Open`.
3. To ensure only the 10 telescope images are added to your sequence, enter "`2008`" in the field `File name contains` and then click `OK`.
4. The new window will display your FITS image stack. If you're having trouble seeing any stars, try clicking the `Auto Brightness and Contrast` and/or `Image Negative` buttons shown below.

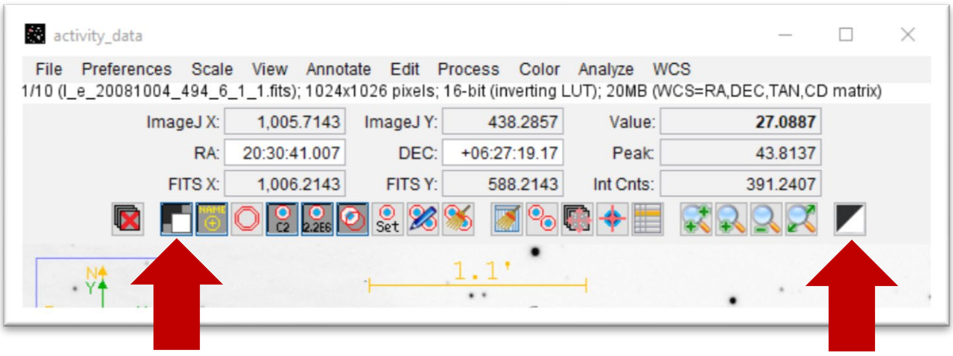


Figure 2: AstroImageJ UI

5. From the main *AstroImageJ* toolbar, click on `File > Open` and select the `finder_chart_Wasp_2.jpg` file and compare it to the FITS image to identify the **target** and the **reference star**.

6. From the FITS image stack window, click on the `Change Aperture Settings` button and input the values below. All other settings can be left on default.

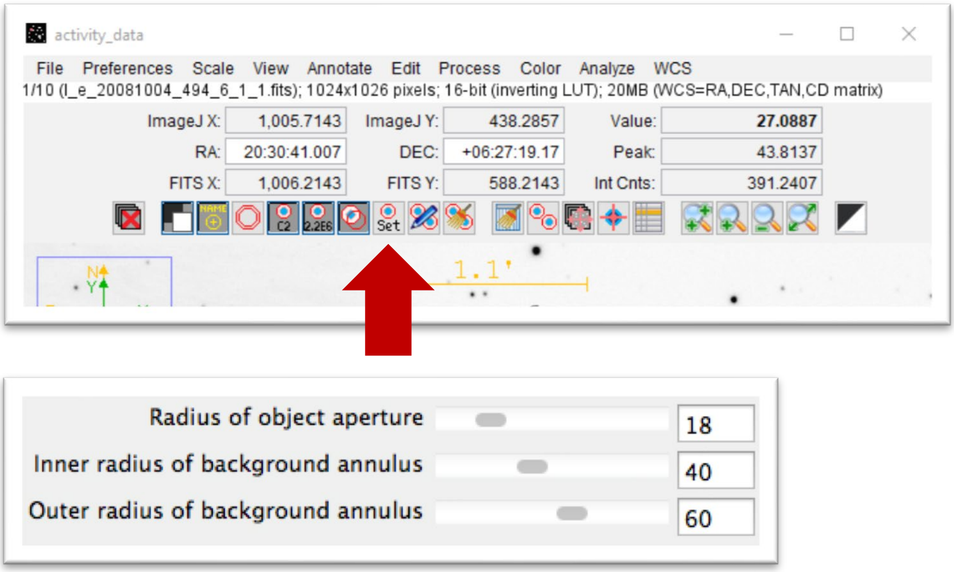


Figure 3: AstroImageJ Aperture Settings

7. From the *AstroImageJ* window, click on `Image > Show Info` and take note of the start time of the observation (**UTSTART**). As shown below, record this time, as it's exactly shown in the info box, in the first empty cell of the excel spreadsheet.

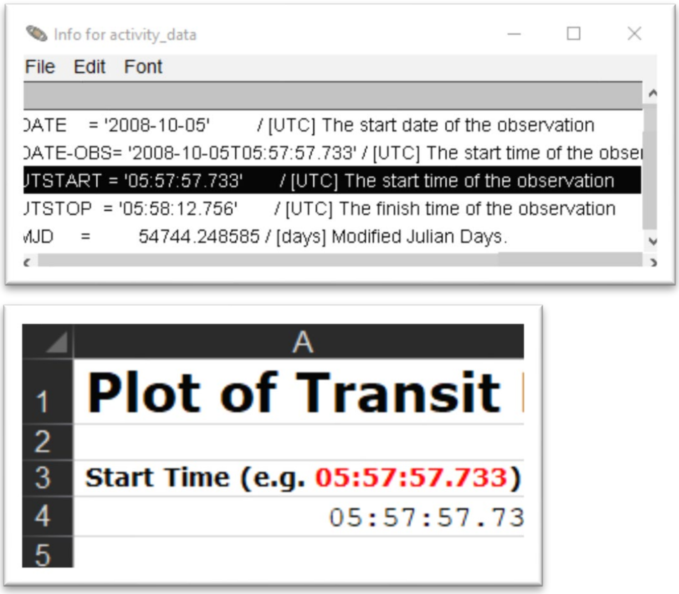


Figure 4: Entering the time data into the spreadsheet

8. From the *AstroImageJ* window, click on the `Aperture Photometry Tool` button and then select the target star, followed by the reference star. A new measurements window will be displayed.

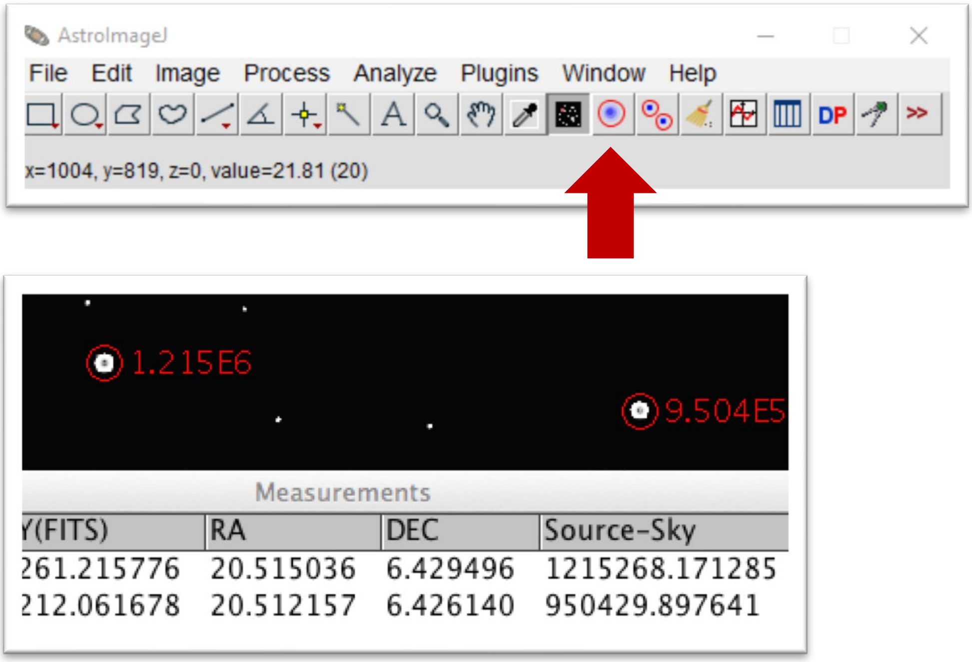


Figure 5: Entering photometry data into the spreadsheet

9. Record the `Source-Sky` value (the intensity) of both the target and reference star in the provided excel spreadsheet. The spreadsheet should automatically calculate the `Source / Reference` and `Relative Intensity` values. It should also plot your first data point as a red diamond.

10. Clear your aperture selections by clicking on the `Clear Apertures` button, shown below.

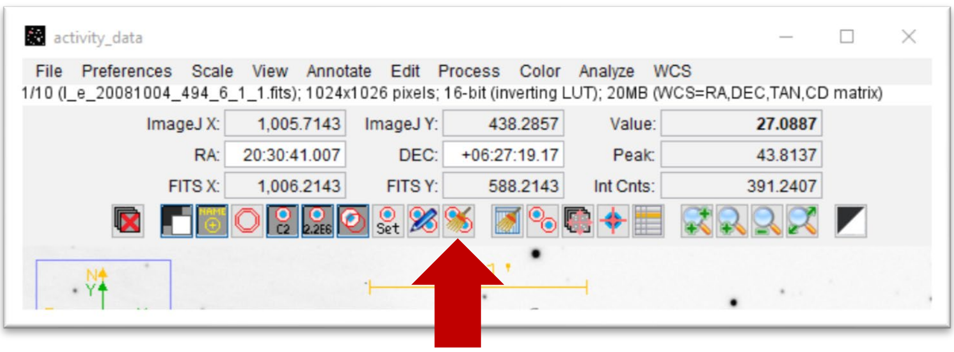


Figure 6: AstroImageJ clear apertures

11. Repeat steps 7 to 9 for the remainder of the FITS frames. You can change FITS frames by dragging the scroll bar on the bottom of the image window. Remember, if you're having difficulty seeing the other FITS images, try clicking on the `Auto Brightness and Contrast` and/or `Image Negative` buttons.

Analysis

Mass and Luminosity of a Star

The Hertzsprung-Russell diagram is a plot of luminosity vs. temperature for stars. The luminosity is noted both in multiples of the Sun's luminosity and in and in absolute magnitude. By making observations, one can work out where a star sits on the diagram, thus working out its luminosity.

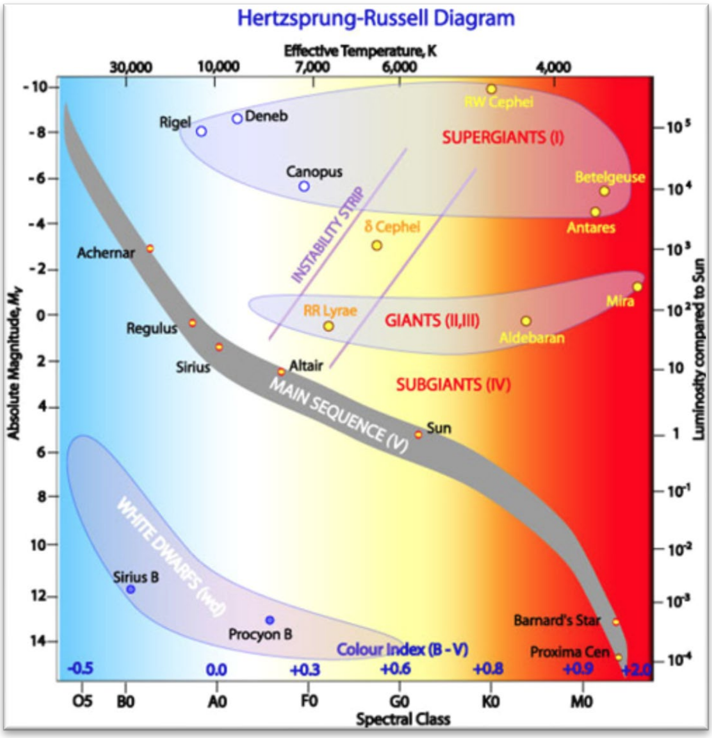


Figure 7: Hertzsprung-Russell diagram

For main sequence stars (of which our Sun is a member), the luminosity increases with the mass with the approximate power law:

$$L_* = L_\odot \left(\frac{M_*}{M_\odot}\right)^4$$

Where $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun, and $L_*$and M_* are the luminosity and mass of the star. Since we know the mass and luminosity of our own Sun and we know the luminosity of the star, we can work out the star's mass by rearranging the equation:

$$M_* = M_\odot \left(\frac{L_*}{L_\odot}\right)^{\frac{1}{4}}$$

The Hunt for New Worlds

Department of Physics and Astronomy

Question 1

How did your light curve turn out? Comment on what's happening to the intensity of the target star (aka WASP-2) over time and why?
This method only works for star-planet systems that have orbits aligned in such a way that,
as seen from Earth, the planet travels between us and the star and temporarily blocks some
of the light from the star once every orbit.

Question 2

Given the mass of our Sun is 1.989×10^{30} *kg*, the luminosity of our Sun is 3.85×10^{26} *W* and the luminosity of our target star, WASP-2 is 2.2×10^{26} *W*, **calculate the mass of WASP 2**. How much is this in terms of the Sun's mass? (Hint: use one of the equations above)
M_* = M_sol (L_*/L_sol) ^ (1/4)
M_* = 1.99 × 10 ^ 30 ((2.20 × 10 ^ 26) / (3.85 × 10 ^ 26)) ^ (1/4)
= 1.72 × 10 ^ 30 kg
= 0.86 M_sol

M_* (kg) = 1.72 × 10 ^ 30 kg	M_* (in $M_\odot$) = 0.86 M_sol

Question 3

Thanks to multiple observations, the orbital period for this exoplanet, WASP-2b is known to be **2.152 days**. From stellar classification from the Hertzsprung-Russell diagram, we have calculated the mass of WASP-2. Assuming WASP-2b is in a circular orbit, use Kepler's Third Law to **calculate the orbital radius or distance WASP-2b is from its host star, WASP-2**:

$$\frac{4\pi^2}{T^2} = \frac{GM_*}{d_{\mathrm{orbit}}^3} \rightarrow d_{\mathrm{orbit}} = \sqrt[3]{\frac{GT^2M_*}{4\pi^2}}$$

Where T is the exoplanet's orbital period in seconds, M_* is the star's mass, G is the gravitational constant (6.67×10^{-11} m^3 kg^{-1}s^{-1}) and d_{orbit} is the orbital radius in metres. Convert your answer to AU (astronomical units). 1 AU = 149 597 871 km.

d_orbit = (185,930 ^ 2 s · 6.67 × 10 ^ (-11) m ^ 3 kg ^ (-1) s ^ (-2) · 1.729 × 10 ^ 30 kg) / (4π ^ 2)) ^ (1/3)

d_orbit = 4.65 × 10 ^ 9 m

d_orbit ≈ 0.03 AU

d_{orbit} (metres) = 4.65 × 10 ^ 9 m	d_{orbit} (AU) = 0.03 AU

Planet Habitability

The distance of a planet from its star gives us crucial information about its possible habitability. In particular, we're looking for planets that lie in the star's habitable zone – a region not too hot and not too cold. The temperature must be in the range to allow for liquid water, which is an essential ingredient for nearly all life forms that we know of. If the planet is too close to its star, all water vaporises, and if the planet is too far from its star, water is all frozen.

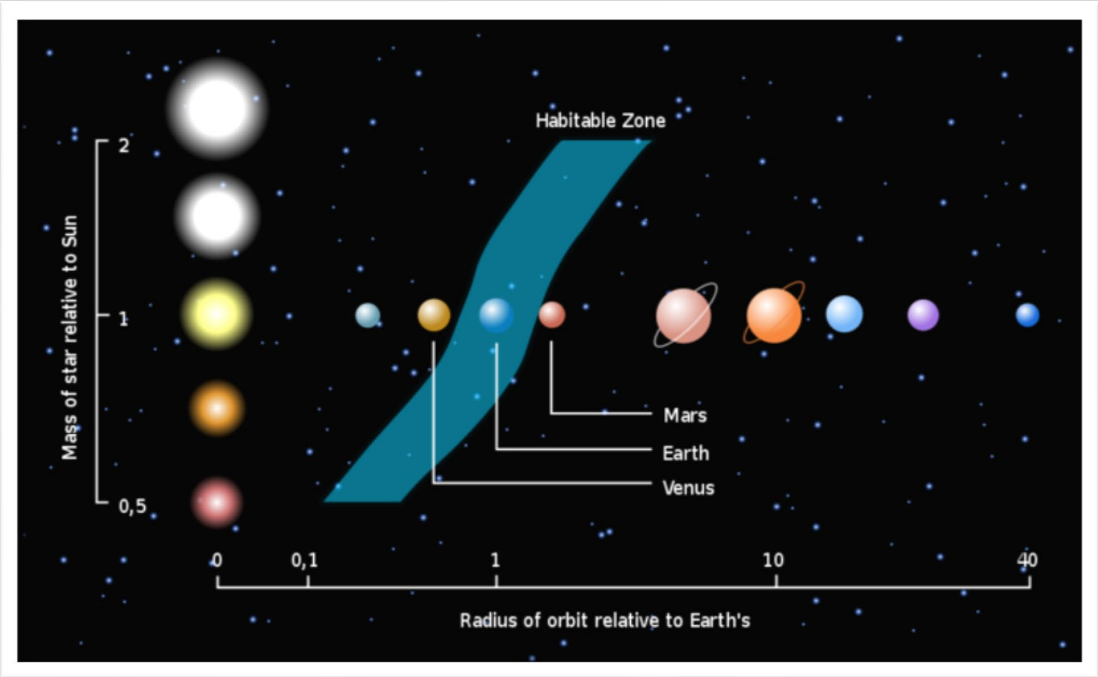


Figure 8: Habitable zone relative to size of star

The size and location of the habitable zone is directly related to the luminosity of the stars. Most models place it at a range of 0.94 to 1.72 AU from the Sun. Using the inverse square law, the range of a habitable zone for different stars can be given by the two equations below.

$$d_{\text{inner}} = 0.94\sqrt{\frac{L_*}{L_\odot}}\,\text{AU} \qquad d_{\text{outer}} = 1.72\sqrt{\frac{L_*}{L_\odot}}\,\text{AU}$$

Where L_* and $L_\odot$ is the luminosity of the star and Sun respectively, and d is the distance to the habitable zone edge, in astronomical units.

Question 4

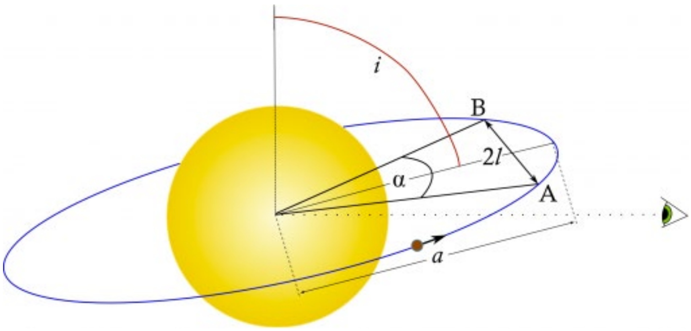
Calculate d_{inner} and d_{outer} for WASP-2. Is the exoplanet, WASP-2b within the habitable zone of its host star, WASP-2?
d_inner = 0.94 √ ((2.20 × 10 ^ 26) / (3.85 × 10 ^ 26)) AU
d_inner = 0.71 AU
d_outer = 1.72 √ ((2.20 × 10 ^ 26) / (3.85 × 10 ^ 26)) AU
d_outer = 1.30 AU

d_{inner} (AU) = 0.71 AU	d_{outer} (AU) = 1.30 AU

Planet Habitability

The radius is also a crucial parameter when classifying exoplanets. For example, if the planet is too small (like Mercury or Mars), it will not have enough gravity to hold on to an atmosphere - gas molecules will escape the planet over a time-span of not many years in the lifetime of the planet-star system. If the planet is too large, it will retain a huge amount of atmosphere and have crushing atmospheric pressure, like the giant planets Jupiter and Saturn. In addition to this, when transit measurements are coupled with measurements from other detection methods, the radius can help us determine the mass, density and even the composition of the planet. All of this provides us with crucial information about its possible habitability.

From the light curve plot, we estimate the transit of our planet to take **1.8 hours** with a dip in brightness of **2.00%**. We also assume an edge-on orbit (**90° angle of inclination**) and the following:



$$t_{trans} = \frac{T}{\pi}\sqrt{\left(\frac{R_*}{d_{\text{orbit}}}\right)^2 - \cos^2(i)}$$

$$\frac{R_P}{R_*} = \sqrt{dip}$$

where t_{trans} is the transit time in seconds, T is the exoplanet's orbital period in seconds, d_{orbit} is the orbital radius in metres, i is the inclination and R_* is the stellar radius in metres.

Question 5

Calculate R_P, the radius of the exoplanet. Express the orbital radius in terms of a multiple of the radius of Jupiter, R_J, given that R_J = 69 911km. (Hint: calculate R_* using the first equation, and then use it in the second to calculate R_P)

Need another hint? Given the inclination is zero, the first equation can be simplified to:

$$t_{trans} = \frac{T}{\pi}\sqrt{\left(\frac{R_*}{d_{\text{orbit}}}\right)^2 - \cos^2(90°)}$$

$$t_{trans} = \frac{TR_*}{\pi d_{\text{orbit}}} \rightarrow R_* = \frac{\pi d_{\text{orbit}} t_{trans}}{T}$$

Question 5 Cont.

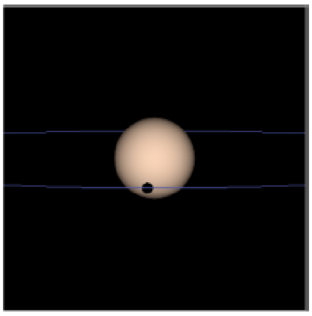
t_trans = T / π √ ((R_* / a) ^ 2- cos ^ 2 (90°))
t_trans = (TR_*)/πa → R_* = (πa t_trans) / T
R_* = (π·4.65 × 10 ^ 9 m · 6,480 s) / (185,930 s) = 5.09 × 10 ^ 8 m
R_* ≈ 0.73 solar radius
R_P/R_* = √dip → R_P = R_* √dip = 5.09 × 10 ^ 8 m · √ (0.02)
R_P = 7.20 × 10 ^ 7 m ≈ 1.04 R_Jupiter

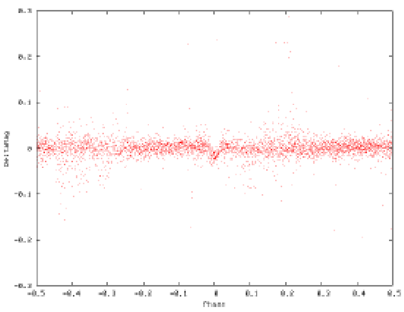
R_P (metres) = 7.20 × 10 ^ 7 m

R_P (in R_J) = 1.04 R_Jupiter

This activity represents a basic approach to plotting a light curve of a transiting exoplanet. As such, your results are merely rough approximations. More highly detailed results of WASP-2b, collected by tge survey team, SuperWasp, are shown below.

WASP-2





SWASP Identifier	1SWASPJ203054.12+062546.4
Apparent Visual Magnitude	11.9
Distance from Earth	470 Light Years
WASP-2 Spectral Type	K1V
WASP-2 Photospheric Temperature	5080K
WASP-2 Radius	$0.81 \pm^{0.02}_{0.02}$ Solar Radii
WASP-2 Mass	$0.86 \pm^{0.02}_{0.02}$ Solar Masses
WASP-2b Radius	$1.05 \pm^{0.04}_{0.04}$ Jupiter Radii
WASP-2b Mass	$0.89 \pm^{0.03}_{0.03}$ Jupiter Masses
Orbital Distance	0.0310 AU
Orbital Period	2.152 Earth Days
Planetary Equilibrium Temp. (A = 0)	1235 K
Mid-point of Transit	2454002.27540 HJD

Question 6

Compare your results of WASP-2b to data from the survey team of SuperWASP and reflect on how this experiment could be improved to enable better characterisation of the exoplanet.
> It is clear to see from the FITS stack that the CCD camera generated unwanted noise.
Subtracting this would improve measurements on the target and reference stars.
> The CCD can also cause bias voltage and other unwanted variations. Calibrations, including
bias frames and subtracting the flat-field frames can help correct for this.
> Add more reference stars.
> Include more data points and multiple orbit observations.

Question 6

Using your calculations and assuming WASP-2b's star is our Sun, do you think WASP-2b would be habitable? Explain your answer.
d_orbit (AU) =0.03 AU
d_inner (AU) =0.71 AU
d_outer (AU)= 1.30 AU
Not within the habitable zone. Wasp-2b is too close to its host star!

Acknowledgements

The experiment is based on the work by Cowley & Hughes 2014.