PXT992 Project Plan
Assessing our Capabilities and Ability to Detect Exomoons Around Gas Giant Planets

Supervised by Subhajit Sarkhar

Liam Hall

1 Introduction

1.1 Overview

The ability to detect exomoons will help us to understand the varying planetary systems, their formation and their evolution. Depending on their position, moons can create both stability and instability in regards to their parent planet (i.e. our Moon stabilises the Earth's rotational axis and precession [1] which supports the life on this planet) and a select few moons in our solar system are theorised to have liquid oceans beneath the surface which leads to the question: are those moons habitable? Subsequent research would analyse our capabilities to be able to detect exomoons by designing simulated systems of planets and moons around different stars within the circumstellar habitable zone (CHZ) and testing the potential to detect such systems or possibly even building an entire new observatory specifically for exomoon observations and habitability testing. Studying our solar system, it is safe to assume that there is a very high ratio of moons to planets around other stars and so the chances of finding an exomoon with suitable conditions within the CHZ will improve. The following questions we hope to answer in this research project will help determine how close we are to being able to detect these relatively small bodies hundreds of light years away from us since there has not been any form of detection of exomoons to date [2].

1.2 Research Questions

These are the questions we want to answer whilst completing this research:

- Can we identify transiting exoplanets which are most likely to have detectable exomoons in the habitable zone?
- Can we assess the capability of the James Webb Space Telescope (JWST) or other instruments to detect exomoons in the habitable zone?
- Can we assess if transit timing variations (TTV) or transit photometery is the better technique for exomoon detection?
- Which characteristics of exomoons are more detectable?

1.3 Aims and Objectives

Aim 1 - Data mining to create a list of giant planets in the habitable zone:

Objective 1.1 Using NASA's Exoplanet Archive to identify planets residing in the habitable zone.

Objective 1.2 Filter these possible habitable planets and condense the list into planets that are detected via the transit method.

Objective 1.3 Filter those further by getting radius/mass measurements and only having planets with radii or mass with the likes from Neptune to larger than Jupiter.

Aim 2 - Building a simulation framework:

Objective 2.1 Orbital simulation - Create an orbital model of moons around planets with factors such as mass, radius and separation which will affect the orbital properties (using a 15m telescope).

Objective 2.2 Light curve simulation - Simulate a light curve for a given planet and its moon, with the movement affecting this curve. (The light curve simulation will rely on the orbital simulation).

Objective 2.3 Noise simulation - Create a noise model of the star-planet-moon system as a function of the instruments and detectors.

Aim 3 - Build a detectability test:

Objective 3.1 Test the effectiveness of our capability in detecting the moons with light curves and assess if any particular conditions are needed.

Objective 3.2 The transit timing variations will be fitted to the model of the orbital simulation to find t_0 - the time at the start of the transit. Each planet and moon will have varying parameters such as separation and their mass-radius relationship.

Objective 3.3 Identify these parameters which are detectable.

Objective 3.4 Find the probability that these moons may be detectable given the parameters and conditions.

Aim 4 - Final list of candidates:

Objective 4.1 From the information gathered from the previous objectives, a prioritised list of candidates are made which will be used for follow-up observations and for further research on these planets to try and detect exomoons.

Aim 5 - Comparison with results:

Objective 5.1 Compare results of the filtered list of planets, the simulation frameworks and detectability test with colleague results in order to come to a conclusion if this research was of significance.

2 Literature Review

2.1 Moon Formation

Moons, also known as natural satellites, are celestial bodies that orbit another celestial body that isn't the host star. There are three ways moons can form with the vast majority of those are formed by the accretion of material [3] due to the collapse of the protoplanetary disc forming satellitesimals [4]. In this scenario, the composition of the planet and moon will be similar since they have material from the same part of the disc. The second way for a moon to form is known as the solids enhanced minimum mass model (SEMMM) [5] where the moons form as soon as there is enough free material caused from the vaporisation of the planet's surface and/or atmosphere (ablation) and fragments of the planet accreting to form the satellitesimal. Thirdly, Crida and Charnoz (2012) explains how a moon forms within the outside of the Roche limit of a planet and possibly migrate outwards to a more stable orbit. A great example of this is Saturn's ring system - the ring, made up of ice, dust and rocks, lie within the Roche limit of Saturn and so the tidal forces are greater than the individual gravitational force of a body within the rings to coalesce, forming a satellitesimal [6]. Moons can also form in different areas of a protoplanetary disc, outside the Hill Sphere[1] [7] of any other planet or body. The Moon is believed to have been formed this way, a theory known as the Giant Impact Hypothesis. In the early solar system, a Mars-sized planet named Theia, having a similar orbit to Earth, eventually collided which resulted in the formation of the Moon from the remnants of the collision and also giving the Earth's axial tilt, hence our seasons [8].

Looking at the only reference we have, the solar system, we see dozens of moons orbiting the ice and gas giants of which have masses between $14M_\oplus$ [9] and $318M_\oplus$ [10]. These ice and gas giant planets dominate the solar system with moons, with three additional moons orbiting the innermost terrestrial planets: Earth's moon and Mars' moons Deimos and Phobos. It is intuitive and safe to assume that this is the case for other system in the Milky Way and the rest of the Universe offering a high probability that life will exist elsewhere. Astrophysicists hypothesise that there are quite a few moons in our solar system that could have the right conditions for life, albeit, microbial life, namely Europa, Ganymede, Titan and Enceladus which are some of the largest of the moons orbiting Jupiter and Saturn. These moons have been the centre of attention over the past decade since it is theorised that they could harbour life beneath their thick layers of surface ice [11, 12]. These moons are thought to have oceans beneath this ice which are heated internally by tidal frictions caused from the close separation to their respective planets or the residual heat from the early stages of planetary and satellite formation. The thick layers of ice help protect the sub-surface layers from harmful radiation emitted by Jupiter and Saturn from the energetic charged particles in the magnetic fields [2, 13].

2.2 Habitability

When talking about habitability or circumstellar habitable zones (CHZ), this would be the area surrounding a star where, given the right temperature and pressure conditions on a planet (or moon), water ice is able to melt or condense and be in a stable state.

For Sun-like stars (spectral class G), we know that the habitable zone lies within 1 AU [14] and for smaller, lower spectral class stars this habitable zone will be less than 1 AU and greater than 1 AU for higher spectral class stars since the power output will be different for each star.

For life to exist, our current understanding is that a planet has to be within the CHZ and have a source of food and water but as previously mentioned, there are a select few moons beyond Jupiter's orbit that could have a slight possibility of being habitable. This is due to some local processes that happen within the moons themselves, which have the right conditions for the presence of liquid water. On Earth, some bacteria is known to feed off hydrothermal vents at the bottom of the ocean which often rises to 400°C and anaerobic bacteria feeding off and gaining energy from sulphur, hydrogen and iron-rich sources [15]. These new and different ways for life to exist opens up many possibilities that

[1] The Hill Sphere being the region surrounding a mass where the gravitational force dominates local space and attracts smaller bodies.

life *will* exist elsewhere in the solar system and surrounding other stars which begs the question: why haven't we detected life? Studies suggest that life forms (i.e. microbial life) could be found in the permafrost or icy regions of planets and moons, surviving for long geological periods of time [16, 17]. With the theory that Europa and Enceladus may have internal heat beneath the surface, the chances of finding life in these regions are somewhat higher than what they were a few decades ago.

Studying the solar system gives a better understanding of what we could find in other star systems, and that we should not be limiting ourselves to what we do know about the survival of life when there are only microbes surviving in conditions that are not favourable by the majority of life. It is imperative to keep an open mind when discussing the habitability of other planets and moons as there is evidence on Earth and possible evidence on the moons of Jupiter and Saturn.

2.2.1 Why are exomoons important?

After discussing formations and which moons have the slightest possibility of being habitable in our own solar system, the chances of having habitable exoplanets and exomoons are even higher. There are several reasons as to why the detection of exomoons are important:

1. Formation of moons – Looking at exomoons and simulating planetary systems with additional bodies gives us a chance to understand the collapse of protoplanetary discs and planetary formation in the early stages of a star system's life.

2. Habitability – Discovering a habitable world is what all astronomers dream of and so with the knowledge that we have about our own solar system and the potential to have as many as 5-6 worlds surrounding one star, it would be naive of us to think that there is no life elsewhere. With the ratio of moons to planets being that much higher, the likelihood of finding a habitable exomoon is ever greater.

3. Effects on planets – Moons are known to have an effect on the planet they orbit. The Moon creates the tides, slowing the rotation of the Earth, and other moons can change other characteristics of planets which will help with the understanding of planetary evolution.

4. Detection methods – The task of detecting exomoons can drive the development of new technologies that allows us to observe deeper into the universe as exomoons are relatively small and so are difficult to detect.

2.3 Detection methods

Our first step towards detecting exomoons is to detect exoplanets. There are various methods in which it is possible to detect exoplanets and each all have their advantages and disadvantages.

2.3.1 Transit Method

The transit method is probably the most common detection method for exoplanets. For an exoplanet to be detected, the orbital plane has to be aligned with the line of sight of the observer and the star in order for the planet to pass in front of the star, or 'transit'. This in itself is a disadvantage since it cannot detect systems that have orbital planes perpendicular to the line of sight. The observations taken from a transiting planet measures the flux or magnitude of the star and is plotted in a light curve against time. The dip in magnitude, known as the transit or fractional depth, D_t, tells us the radius of the planet if the radius of the star is known using the ratio of the planet's area to the area of the star:

$$D_t = \left(\frac{R_p}{R_s}\right)^2, \tag{1}$$

where R_p and R_s is the radius of the planet and star respectively.

Another problem with transiting planets is the probability (P_{tr}) of one actually transiting. This is given by:

$$P_{tr} = \frac{R_s}{a} \tag{2}$$

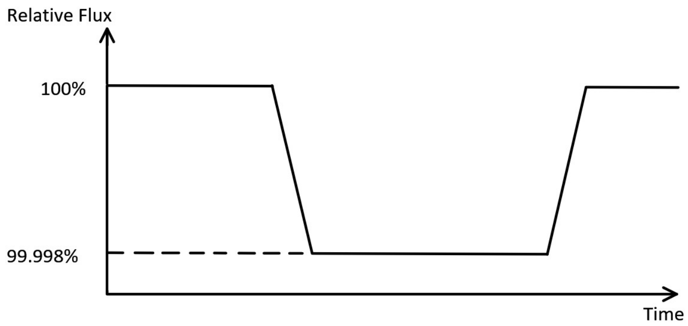

Figure 1: Here is an example of a basic light curve without data points, but a basic fit. It shows the relative flux of the star against time, whether that be hours or days depending on the exoplanet's orbital period and radius. Assuming the star has radius similar to that of our Sun ($1R_\odot$), and given the transit depth, $D_t = 0.002\%$. By using equation 1, the radius of the planet will be: $0.00002 = (R_p/1R_\odot)^2 \rightarrow R_p = 1R_\odot \times \sqrt{0.00002} = 0.0045R_\odot$ or 4% the radius of Jupiter.

where a is the semi-major axis of the orbiting planet and assuming a circular orbit. Presume we're trying to observe a planet with a similar radius to that of Jupiter, and has an orbital period of 3 days, the probability of a transit of a Sun-like star is roughly 10% [18].

2.3.2 Transit Timing Variations

In addition to the transit method, the transit timing variations (TTV) is a way of detecting unseen exoplanets within the same system, as the assumed periodic orbit of one planet is either earlier than expected or later than expected. This is due to the fact that these planets are interacting with one another by exerting their gravitational force, changing their orbital velocities. If the known planet is early in its transit, we can infer that the other planet(s) are ahead of this one and vice versa.

The transit timing variation method allows for the indirect detection of an exoplanet that would not otherwise be detected by normal means (i.e. radial velocity or transit). The variation of the transit times depend on the mass of the non-transiting planet and its orbital period, where if the mass is quite high, then the variations will deviate more and if the orbital period is much smaller than the detected exoplanet, the TTV signal will be greater. Having the orbits of the planets in resonance will cause the variations to become much more predictable and thus easier to detect [19].

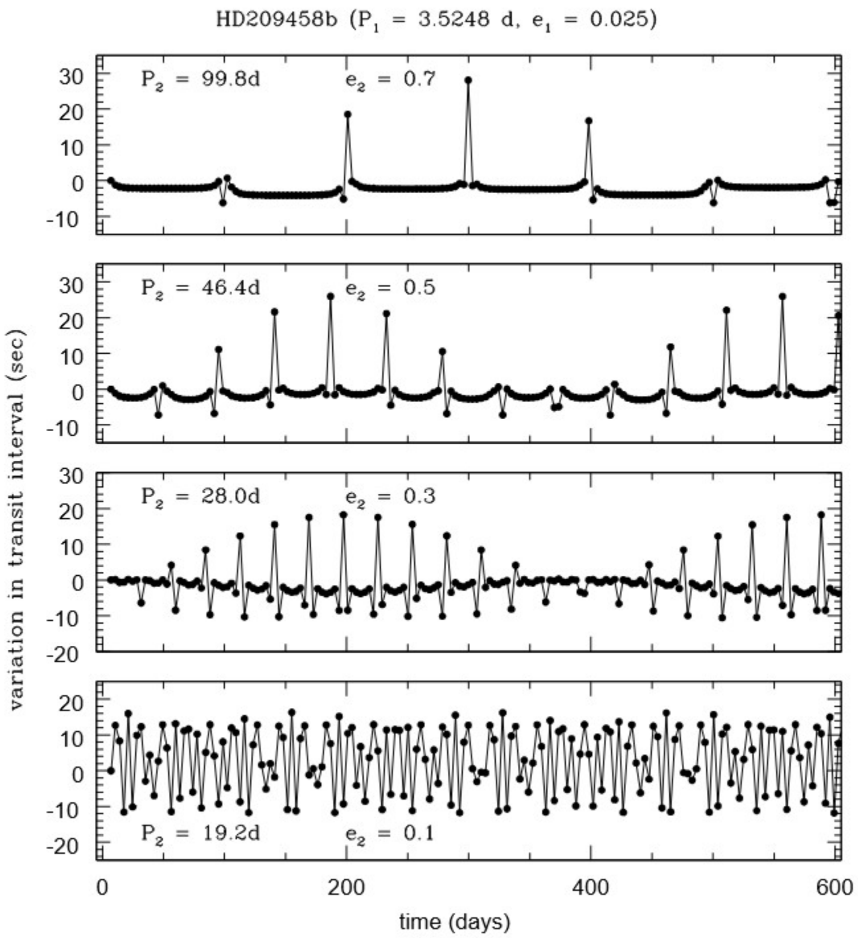

Figure 2: Holman and Murray (2004) created transit variation graphs using the exoplanet HD 209458b from a hypothetical unseen planet. It shows that this second planet will affect the transit timings of HD 209458b by a maximum of 30 seconds [20].

2.4 Observatories

2.4.1 Wide Angle Search for Planets

The Wide Angle Search for Planets (WASP) consists of two ground-based observatories on the island of La Palma and South Africa that utilises eight telescopic cameras each to survey the sky, looking for transiting planets. The approach WASP has taken to detecting transiting exoplanets has proven to be highly successful, leading to the discovery of many exoplanets. WASP is known to detect a large amount of exoplanets and since WASP observes regularly, it can keep a record and time the periodicity of the transiting exoplanets.

Unfortunately WASP's resolution would not be that great in order for it to detect exomoons since the mirrors are small, hence the need for a much larger, and much more sensitive instrument.

2.4.2 James Webb Space Telescope

The James Webb Space Telescope (JWST) is the newest and the long-awaited space telescope to be launched in the past decade. With its 6.5m diameter mirror, its high resolution imaging capabilities allows for the direct observations of exoplanets and possibly exomoons using state-of-the-art instruments. JWST key science opportunities allows for the spectroscopy of giant planets, super-Earths and sub-Neptunes and terrestrial planets as little as $1M_{\oplus}$ [21]. Spectroscopy of these planets is used to determine the composition of the atmospheres, and can explain how it changes with respect to the planets mass. Beichman et al (2014) explains that as of writing their paper, we have had the same knowledge of exoplanets for the last 50 years from observations of our own solar system, and so the observations JWST will make will 'obtain a much better characterisation of the atmospheres of exoplanets, including vertical structure, elemental and molecular abundances, surface gravity, and the effects of non-equilibrium and/or photochemistry' [21].

3 Methodology & Plan

3.1 Meetings

We expect a minimum of 1 weekly meeting as soon as the first week is upon us, where we will discuss what has been done, any issues we might have come across and can be used as an opportunity to gain support and discuss future work that needs to be done before the following week. The dates of the meetings will be decided closer to the time.

3.2 Schedule of Work

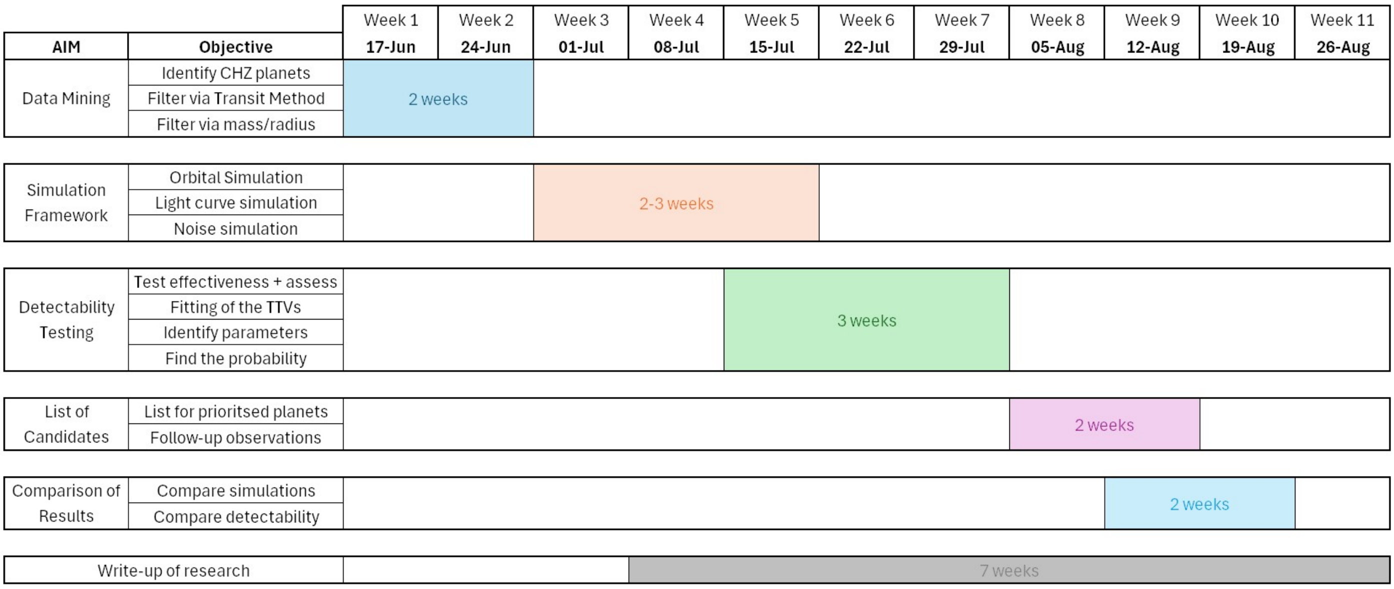

Figure 3: This Gantt chart will represent the schedule of work and how I plan to undertake this research on exomoons. CHZ and TTV is Circumstellar Habitable Zone and Transit Timing Variation, respectfully. An updated Gantt chart will be released with the results of this research at the end of Week 11 to show if the timing of these objectives were achievable and successful.

Data Mining - Aim 1

The first two weeks of the project, commencing the 17th of May, is where we use NASA's Exoplanet Archive to filter down the list of known exoplanets that are within the circumstellar habitable zone, have a mass similar to that of the gas giant planets in our solar system which are detected using the transit method.

Downloading the CSV file of the archive and importing it into Python [22], and displaying that as a dataframe using the Pandas package [23] to then filter the exoplanets by transit method. Using a Python function that we will be required to create ourselves using equations that will determine the habitable zone of each star so it can filter out any planet that orbits their host star outside of this range. The next process would be to filter out planets that are not classed as 'gas giants' by creating a *for*-loop or an *if*-loop which will callback the masses to be read and *if* these exoplanets are not in the range of gas giant masses, then the exoplanet will be discarded. If we were to hazard a guess as to how many exoplanets there will be at the end of these processes, we will expect no more than approximately 50 exoplanets, which will serve as a very generous sample size for the rest of our research.

Simulation Framework - Aim 2

The next task is estimated to be completed within two weeks, and the task is to create three frameworks of simulations: an orbital model, lightcurve simulations and a noise model.

By exploiting the exoplanet and star parameters taken from the filtered archive, it will be possible to create a model or simulation of the planets, assuming they all have circular orbits, around their host star. Afterwards, we will create the same models with hypothetical moons that have varying masses, radii and separation distances to see what effects they have on the modelled exoplanets.

Expanding on these models, light curves will be simulated to see how the varying parameters of the moons and their conditions change over time, observing how they might affect the transit depth and transiting times, which will allow us to gain a better understanding of how easy (or difficult) it in detecting exomoons. This analysis will be in progress by week 5 (the week commencing 15th July).

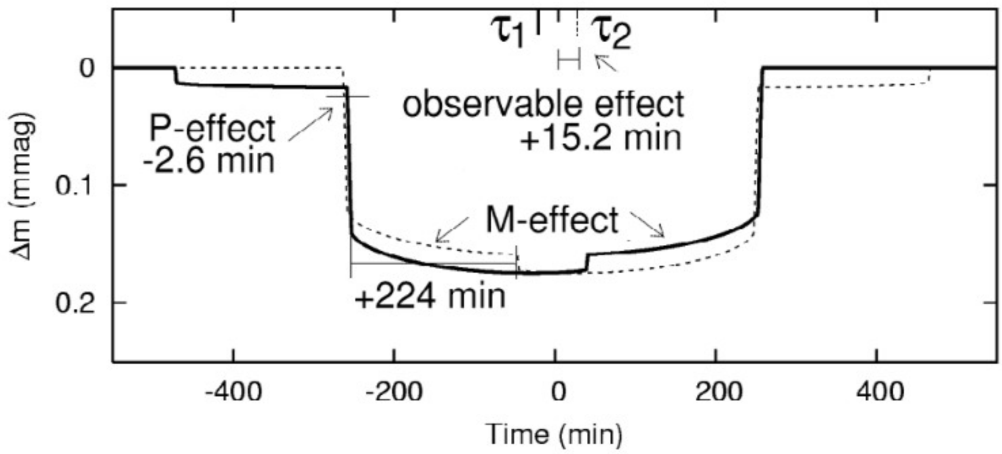

Figure 4: This is an example light curve of a hypothetical moon where the solid line and dashed line is the planet and moon transiting respectively [24] showing the time difference between the two of 15.2 minutes. This is what we aim to achieve for **Aim 2**.

Detectability Test - Aim 3

The detectability test would be built to analyse the light curves of both the exomoons and the exoplanet, comparing that to the orbital models as previously stated, allowing for the evaluation the specific conditions and correct parameters that may affect the light curves and ultimately our detection capabilities. The refinement of the light curve and simulations will determine t_0, the transit time centre. An iterative process will be completed, adjusting the orbital separation, masses and periods of the exoplanets and moon to find the best parameters to allow for the best chances of detecting exomoons. These tests will help to answer the first and last questions on section 1.2: Can we identify transiting exoplanets which are most likely to have detectable exomoons in the habitable zone? and which characteristics of exomoons are more detectable?

List of Candidates - Aim 4

Throughout the research project, from mining the exoplanet archive to building a detectability test, the penultimate goal is to assess whether current observatories such as the James Webb Space Telescope, are able to detect exomoons hundreds of light years away answering the 2nd research question in section 1.2. In the case of coming to the conclusion that current observatories are unable to detect exomoons, whether that be because their resolution is too small or the instruments are not sensitive enough to detect either the reflected light or the change in flux when the moon is transiting, it would be beneficial to discuss potentially new instruments and observatories that would be capable of doing so and it would be essential to assess why our current technological capabilities present any limitations on our detection abilities. A list of candidates will be created which will be used for any possible follow-up observations for the future.

Comparison - Aim 5

Week 9 will see the start of the comparison of results with colleagues, since we will have done our simulations and detectability tests on different detection methods. This process aims to identify any similarities, differences, trends, and/or patterns among our simulations and tests. The completion of the detectability tests on the transit photometry method and the transit timing variation method will allow us to visualise the differences (if any) on how effective these methods are at detecting exomoons which will answer the third research question in section 1.2.

Write-up

Throughout this entire research project of 11 weeks, there will be a weekly write up in a research diary to keep track of objectives that are in progress and objectives/aims that have been completed which will allow for an easier write up at the end of the 11 weeks. The Gantt chart, figure 3, claims that the write-up of the research will commence by week 4 (8th July) however, the write-up should start once the first few objectives have been completed which will ease the stresses towards the end. The submission date for the project is presumed to be at the end of week 11, Friday 30th August and so any final meetings with the supervisor will be held before then.

3.3 Risks

Risks are part of everyday life, and a research project is no different. The research side of the project is optimistically aimed to be completed by week 10 (19th August 2024) as seen in figure 3, to allow for some contingencies that may hinder the completion of the project, and allows for more time to write up the progression of the research so far, in case such events may happen.

Since the project is a simulation project, it does not rely on observations of any kind except for the use of NASA's Exoplanet Archive, and so we are lucky that this will not be a measurable risk in the sense that it may cause some setbacks for the project.

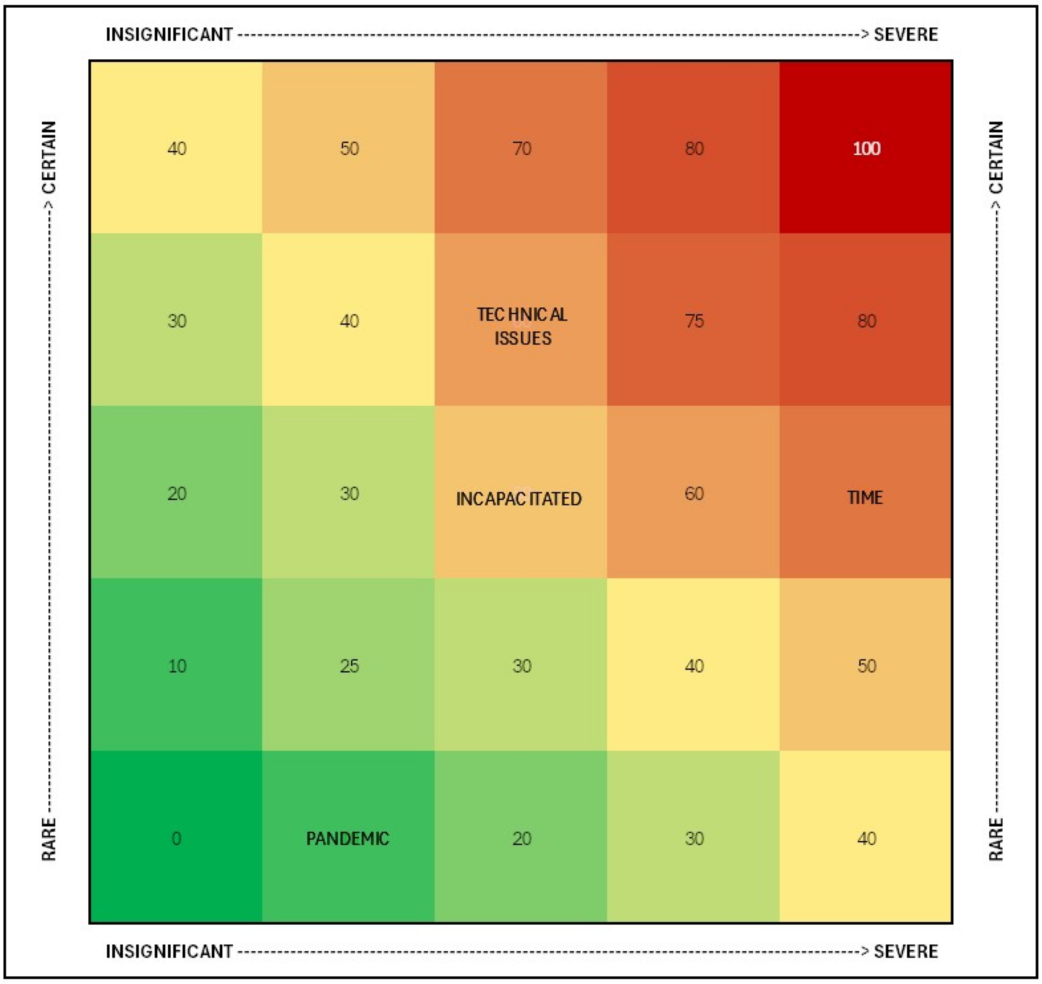

Figure 5: This is a summary of risks using a matrix created to help with the severity and certainty of any risks posed towards this project that may occur within the 11-week time frame.

Here is a list of the possible risks and contingencies in order of least risk to highest risk:

Pandemic

As with recent years, global pandemics are high on the list of risks when it comes to not only research projects, but living day to day. Response from Government officials will be much quicker (in theory) than they were half a decade ago if an outbreak were to ever occur again and although the risk of something along the scale of COVID-19 will be medium to high (2% in a given year [25]) due to increased urbanisation and air travel. With only 11 weeks to complete this project, the chances for a pandemic occurring are cut to 0.42%. Affecting the population and consequently the project will be slim to none because of the preparedness of ourselves, the University and technology that allows for online meetings with supervisors.

Incapacitation

In the unlikely event that either the supervisor or we become ill, injured or unavailable for any serious adverse circumstances, the project will be greatly affected. If we are ill or have been injured which could require hospitalisation, work could continue depending on the severity of how incapacitated we are. If the supervisor has become unavailable, suitable measures will be taken to ensure the support needed will be there by reaching out to other supervisors within the field and the PXT999 module organiser. This is a risk that is quite possible, and depending on the seriousness of the situation it could have quite a severe impact on the project.

Technical Issues

There is always a risk when working with computers and the internet where they are either down or broken. In case this does occur, the coding portion of the project (**Aim 2** and **Aim 3**) will be done on Google Colab via GitHub to keep an online backup of the changes made to the code to ensure that no work is lost. Technical issues can arise at any moment and so the likelihood is quite high, with medium impact on the project. If personal devices are damaged or somehow unavailable, the University will be able to provide laptops through the library or we will have to make use of the computers in the libraries and/or the 4th floor at McKenzie House.

Time

Given that there are 11 weeks in total for the research to commence and the write-up of the dissertation to be completed, time will be one of our greatest adversaries. In order to keep to the schedule of the Gantt chart (see figure 3), it will be necessary to keep an informed diary throughout the project, keeping track of jobs to be completed, having a checklist to hand and referring to the Gantt chart. This will ensure the timely and efficient progress of the project which will keep us on track for completion at week 9.

List of References

References

[1] R. Rast, S. Finney, L. Cheng, J. Schmidt, K. Gerein, and A. Miller, “Effects of the moon on the earth in the past, present and future,” vol. 4, 2017.

[2] R. Heller, D. Williams, D. Kipping, M. A. Limbach, E. Turner, R. Greenberg, T. Sasaki, Bolmont, O. Grasset, K. Lewis, R. Barnes, and J. I. Zuluaga, “Formation, habitability, and detection of extrasolar moons,” vol. 14, no. 9, pp. 798–835, 2014.

[3] P. Bodenheimer and J. B. Pollack, “Calculations of the accretion and evolution of giant planets: The effects of solid cores,” vol. 67, no. 3, pp. 391–408, 1986.

[4] I. Mosqueira, P. R. Estrada, and D. Turrini, “Planetesimals and satellitesimals: Formation of the satellite systems,” vol. 153, no. 1, pp. 431–446, 2010.

[5] A. Crida and S. Charnoz, “Formation of regular satellites from ancient massive rings in the solar system,” vol. 338, no. 6111, pp. 1196–1199, 2012.

[6] E. J. Opik, “Roche’s limit: Rings of saturn,” vol. 1, pp. 25–26, 1950. ADS Bibcode: 1950IrAJ....1...25O.

[7] J. A. Kammer, T. M. Becker, K. D. Retherford, S. A. Stern, C. B. Olkin, M. W. Buie, J. R. Spencer, A. S. Bosh, and L. H. Wasserman, “Probing the hill sphere of (486958) 2014 MU $_{69}$: HST FGS observations during the 2017 july 17 stellar occultation,” vol. 156, no. 2, p. 72, 2018.

[8] R. M. Canup and E. Asphaug, “Origin of the moon in a giant impact near the end of the earth’s formation,” vol. 412, no. 6848, pp. 708–712, 2001.

[9] W. B. Hubbard and J. J. MacFarlane, “Structure and evolution of uranus and neptune,” vol. 85, pp. 225–234, 1980.

[10] NASA Jet Propulsion Laboratory and California Institute of Technology, “Astrodynamic parameters.” https://ssd.jpl.nasa.gov/astro_par.html, 2018. Accessed: 25th April 2024.

[11] C. P. McKay, C. C. Porco, T. Altheide, W. L. Davis, and T. A. Kral, “The possible origin and persistence of life on enceladus and detection of biomarkers in the plume,” vol. 8, no. 5, pp. 909–919, 2008.

[12] J. Lipps, G. Delory, J. Pitmand, and S. Rieboldta, “Astrobiology of jupiter’s icy moons,” vol. 5555, 2004.

[13] K. P. Hand, R. W. Carlson, and C. F. Chyba, “Energy, chemical disequilibrium, and geological constraints on europa,” vol. 7, no. 6, pp. 1006–1022, 2007. Publisher: Mary Ann Liebert, Inc., publishers.

[14] H. Lammer, A. Stökl, N. V. Erkaev, E. A. Dorfi, P. Odert, M. Güdel, Y. N. Kulikov, K. G. Kislyakova, and M. Leitzinger, “Origin and loss of nebula-captured hydrogen envelopes from ‘sub’- to ‘super-earths’ in the habitable zone of sun-like stars,” vol. 439, no. 4, pp. 3225–3238, 2014.

[15] E. V. Pikuta, R. B. Hoover, and J. Tang, “Microbial extremophiles at the limits of life,” vol. 33, no. 3, pp. 183–209, 2007.

[16] S. S. Abyzov, R. B. Hoover, S. Imura, I. N. Mitskevich, T. Naganuma, M. N. Poglazova, and M. V. Ivanov, “Use of different methods for discovery of ice-entrapped microorganisms in ancient layers of the antarctic glacier,” vol. 33, no. 8, pp. 1222–1230, 2004.

[17] R. B. Hoover, E. V. Pikuta, D. Marsic, and J. D. Ng, "Anaerobic psychrophiles from alaska, antarctica, and patagonia: implications to possible life on mars and europa," in *Instruments, Methods, and Missions for Astrobiology IV*, vol. 4495, pp. 313–324, SPIE, 2002.

[18] J. T. Wright and B. S. Gaudi, "Exoplanet detection methods," 2012.

[19] E. B. Ford, D. Ragozzine, and et al, "Transit timing observations from kepler. v. transit timing variation candidates in the first sixteen months from polynomial models," vol. 756, no. 2, p. 185, 2012.

[20] M. J. Holman and N. W. Murray, "The use of transit timing to detect extrasolar planets with masses as small as earth," 2004.

[21] C. Beichman, B. Benneke, and et al, "Observations of transiting exoplanets with the james webb space telescope (*JWST*)," vol. 126, no. 946, pp. 1134–1173.

[22] G. Van Rossum and F. L. Drake Jr, *Python reference manual.* Centrum voor Wiskunde en Informatica Amsterdam, 1995.

[23] Wes McKinney, "Data Structures for Statistical Computing in Python," in *Proceedings of the 9th Python in Science Conference* (Stéfan van der Walt and Jarrod Millman, eds.), pp. 56 – 61, 2010.

[24] G. M. Szabó, K. Szatmáry, Z. Divéki, and A. Simon, "Possibility of a photometric detection of "exomoons"," vol. 450, no. 1, pp. 395–398, 2006. Number: 1 Publisher: EDP Sciences.

[25] B. A. Williams, C. H. Jones, V. Welch, and J. M. True, "Outlook of pandemic preparedness in a post-COVID-19 world," vol. 8, no. 1, p. 178, 2023.

References managed by Zotero.