KØBENHAVNS UNIVERSITET

Masters Thesis

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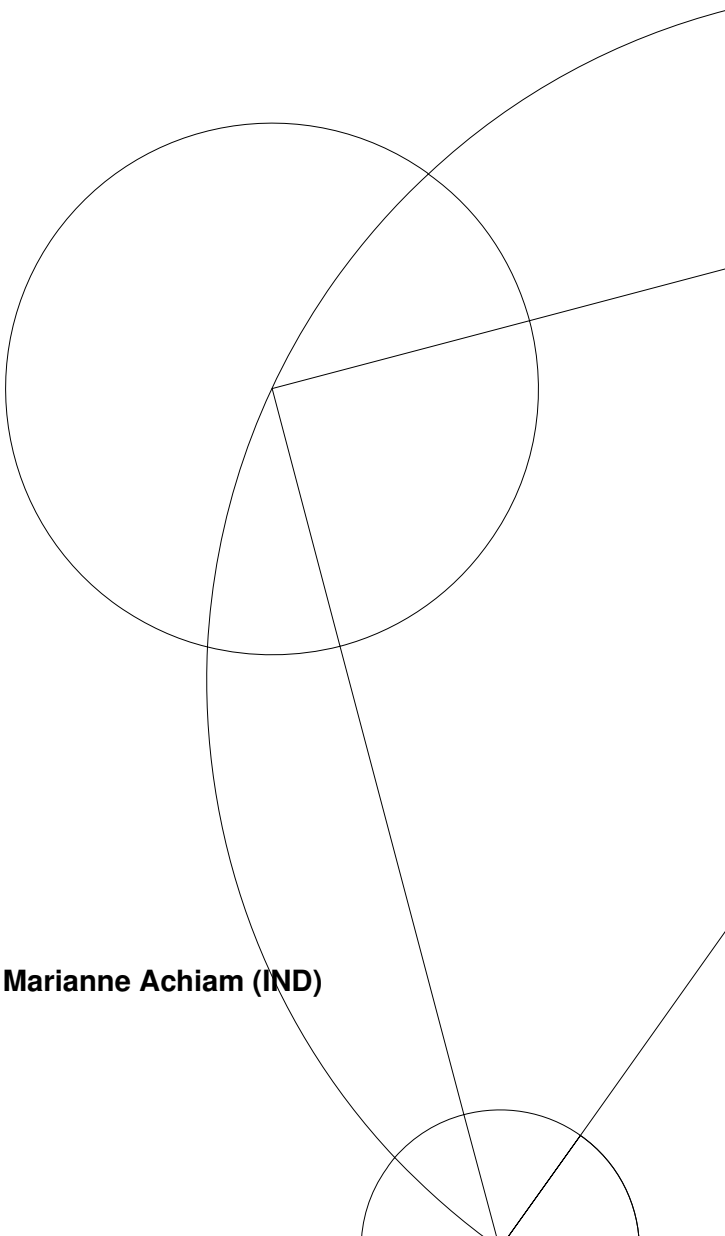
Creating and Testing Astronomy Teaching Packages for an Online Ressource



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Abstract

How do we create relevant and interesting astronomy teaching material and how do high school students solve the given astronomy problems? There are several challenges in teaching astronomy in elementary school and high school. Some of them are that the subject seems easy on the surface, but quickly becomes too complicated, and that the students often lack the mathematical skills needed. Also, the subject can be too abstract or too big compared to the available time for teaching it. Teaching material on exoplanet design has been developed for a high school level course based on di erent considerations for exoplanet observable and derivable properties, such as the orbital period, the planetary mass, size, atmospheric composition and equilibrium temperature, and other interesting considerations, that are not yet derivable with current technology, such as surface and weather of the planet and seasonal periods. The objective of the exercise was to combine the creative aspect of designing an exoplanet as a travel destination inspired by NASA's Travel Bureau posters, while taking di erent aspects into account and use physics to decide some of the properties with realistic values. Before testing the teaching material, a literature review was done on problem- and context-based learning with the focus on ill-structured problems, and using curiosity as motivation for learning, with the focus on science curiosity. The exoplanet design teaching material was then tested with a high school class. One group of three students was observed solving the exercise and the whole class was observed presenting their poster results from the exercise. Prior to the test, a study and research path has been created to map the expected ow of thoughts for solving the exercise, and after the observation an actual study- and research path was mapped based on the actual ow of thoughts during the exercise. After the exercise and presentations a survey was conducted for the whole class, to get an overall idea on what the students especially enjoyed about the exercise and which challenges they had. The result of the observation and the survey showed that the students especially liked the freedom of choice in the exercise, and the balance between the creative aspect and being able to connect the elements using reason based in physics. They were challenged by some of the equations and the time constrain. Based on the results and the study on ill-structured problems and curiosity, improved teaching material was created.

Acknowledgements

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I also would like to thank everyone in the Online Observatory project, with special thanks to Brorfelde Observatory for the opportunity, and the team at Faulkes Telescope Project for inspiring me with their Exoplanet Design package for middle school level.

Furthermore, I would like to thank Kristine Simone Nielsen for letting me use her high school astronomy class as a test subject, and the class itself for their inspiring poster presentations, with a special thanks to the three students, who bravely let me be a fly on their digital wall as part of my experiment.

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Part I

Introduction

How do we create great astronomy teaching material for students? To answer this question, we need to consider the purpose of teaching astronomy. Why is it relevant or interesting and what should the focus of the teaching be? Which challenges are there in astronomy teaching and how can we overcome those challenges to ful ll the purpose of teaching? In this introductory part, I will introduce my thesis, its motivation and purpose, and a preliminary domain research on Danish astronomy education to get an idea of some of the challenges of teaching astronomy.

1 Background and motivation

Although this is a thesis in astrophysics, a great part of it is based on science education due to the didactic nature of creating and testing astronomy teaching packages.

1.1 Background and Online Observatory

The project started as a request for help from The Online Observatory (OO), which was under development as an online educational resource for teaching astronomy with activities targeted elementary school and high school. The project is a collaboration between several European observatories located in: Denmark (Brorfelde), Norway (Solobservatoriet), Finland, UK, and Latvia, and part of the EU Erasmus+ programme.

> Through OO, users can access a variety of educational classroom resources, free software, data archives and even make use of robotic and remotely controlled telescopes located around the world.[1]

There were a total of 8 topics planned for the OO, each with several teaching material developed as a collaboration between the observatories: 1) Observing the sky, 2) Virtual Tours, 3) Small Solar System Bodies, 4) Young Astronomers, 5) The Moon, 6) The Universe, 7) The Sun and Stars, and 8) Planets and Exoplanets.

I started my thesis project with trying to gure out the purpose and target group of the Online Observatory project. A Q&A (in Danish) is attached in appendix A. Basically, the teaching material is meant as free material for middle school and up. It is meant as a motivation and inspiration for teachers to include astronomy as part of the teaching. The packages will be developed in English and thereafter translated to Danish for the use in Denmark. The teaching material should be usable without visiting the observatory, but could include the use of data from the observatory.

1.2 Motivation and purpose

I have always been fascinated by our existence as part of something bigger, and hence the Universe has always been a curious interest of mine. Driven by the inconsistency in the common view on science as dull and many examples of the mainstream search for the truth about the Universe outside the domain of science, I feel motivated to learn not only the physics behind space, but also how we think, talk and teach about the subject.

I did not start a professional interest in astronomy until late in life because I never really thought of astronomy as something that could actually be useful as a choice of career. It was just a subject for a sense of personal wonder. To motivate a purpose of which material to test, with whom, how and why, I rst needed to get better domain knowledge for how astronomy is being taught in school through the whole educational system, and also I needed a general sense of reasoning behind why astronomy education matters for other than personal existential reasons. It is my hope, that being

[1] From OO webpage, https://onlineobservatory.eu (November, 2020)

aware of a larger context for astronomy knowledge will be useful for designing teaching material with the purpose of inspiring students on the astronomy subject.

Hence, the main goal of this thesis is to create astronomy teaching material in one subject and test what happens when it meets the real world in a educational setting. How do the students react to the topics presented? What are they curious about, and what is challenging and discouraging? What can be improved in how the material is taught?

1.3 Structure of the thesis

The thesis consist of five main parts:

Part I is the introduction, including the background, motivation and purpose of the thesis and a second part of preliminary domain research of astronomy education in Denmark. In this part, I mainly look back at the "as is" situation and establish the background settings for the thesis.

In part II, I present the teaching material case, narrowed down to the subject of exoplanets. I will explore the physics behind various aspects of exoplanet observations and derivations of properties, which could be relevant up to high school level. Then I will present the first iteration of the teaching material, used in the following test, including justification for choices, based on the preliminary domain research.

Part III is a literature review of the science education field with main focus on motivating curiosity towards science and astronomy through problem-based learning and the improvement of the teaching material case.

In part IV, I will describe and justify the methodology used for the test and the following analysis of the results and then present the main result based on this methodology.

Part V includes an analysis and discussion of the results relating to the findings in the literature review, an implementation of improvements om the case material based on the discussion, and at last a perspective to further astronomy teaching.

At last, a wrap-up including conclusion of the main findings in the thesis relating to the purpose.

2 Preliminary domain research

For the purpose of the thesis, I did some preliminary research of the domain of astronomy education in Denmark, including the expected learning path and challenges and successes from teachers at various levels. The aim of this was to get an idea of issues and barriers, and nd inspiration for upcoming topic and case for teaching material.

2.1 Danish astronomy education learning path

I have looked into the educational system at di erent levels, summarizing the main relevant learning objective for physics- and astronomy-related topics from middle to high school at the time of this thesis, based on the curriculum included in appendix B.1 to B.1.

2.1.1 Elementary (middle) school

For the elementary school, there are new requiments in 2nd, 4th, and 6th grade (Appendix B.1):

The closest to astronomy in2nd grade is learning about the sun, the night and day, and the seasons. Also, it is expected that the children at this age can distinguish between reality and a model.

In 4th grade, the children will learn about the Earth, the Moon, and the planets in the solar system. They should be able to show the movements of the planets around the Sun, the Moon around Earth, and compare the planets in our solar system through a model. In general the children should be able to construct and understand simple models of the world.

In 6th grade, there is not much new astronomy-relating teaching. Focus is more on nature itself, biology, energy and sustainability, and the geological properties of Earth. In this age, the students should be able to work with composite models to describe processes and be able to discuss the suitability of simple models.

To summarise, elementary school is all about getting familiar with Earth as a planet and in a greater context with the Moon, the Sun and the in uence they have on our everyday life experience, such as day, night, seasons, tides, and other natural phenomena, including Earth sciences such as geology and biology. Also, the students are expected to be trained in modeling reality, from simple to composite models.

2.1.2 High school

In high school, there are three levels of physics, and one level of astronomy:

Physics C is an obligatory course for all 1st year high school students, and can thus be seen as almost a natural continuation and build-upon from elementary school. The main astronomy in this subject is: "The physics contribution to the scienti c worldview"

- basic features of the current physical description of the Universe and its evolutionary history, including the expansion of the Universe.

- The Earth as the planet in the solar system as a basis for explaining easy observable natural phenomena

The second part might overlap and include some recap from elementary school, depending on the exact teachings in both, but certainly a repetition of something, that isn't studied otherwise, is usually a good idea in di erent contexts.

The two other topics that are part of the core material in this course is energy and light, both of which are relevant to the understanding of the Universe and observation of the Universe, although they do not necessarily relate to astronomical topics in the teaching. Light includes the electromagnetic spectrum and absorption and emission of a photon.

Physics B is the rst extra level elective physics course, that builds upon Physics C. In "The physics contribution to the scienti c worldview", there is an addition to the expansion of the Universe with knowledge of spectral redshift.

Teaching energy now includes the kinetic and potential energy in the gravitational eld of Earth.

Teaching about photons is now speci cally taught in the realm of quantum mechanics, and also includes the radioactive decay, which is an important process in stars, and therefore also extra relevant for astronomy teaching.

Another new topic is mechanics, which includes Newton's three laws in one dimension.

Physics A is the highest level of physics that the students can choose in high school. On this level, the mechanics that was taught in one dimension on level B, is now expanded to two dimensions and into the gravitational eld around a central object.

There is also a "surprise" topic every year under the title "Physics in the 21st century". This changes about every 3rd year and is the same topic for every high school in Denmark. Previous topics have included:

- "Plasma physics and fusion energy" (2015),
- "The building blocks of the Universe" (2012),
- "The dynamical stars" (2009).

So it is quite often that it has been about astronomy. The latest in 2018 was about hospital physics, and the previous before 2006 was about laser physics.

Astronomy is an elective course, that does not require other physics than the obligatory level C and mathematics level C. The topics taught are:

- Our (physical) place in the Universe: The solar system, planets, exoplanets and the conditions for life, The Milky Way and other galaxies, the cosmic zoom and distance measurement.
- The evolution of the Universe: The Big Bang model, cosmological redshift, the age of the Universe, the Cosmic Background Radiation, and the creation of the rst elements. Birth of stars and planets, evolution of stars, including the creation of elements. The fundamental elements of nature, including dark matter and black holes.

25% of the course will be supplementary subjects to expand on the core subjects described above. The students should have signi cant in uence on the subjects, and the subjects can be interdisciplinary with other subjects.

The course should also include experimental and observational work, which could be: Own observations of the night sky with or without instruments, data processing of own or other data, analysis and interpretation of data, virtual experiments.

The students will be making a personal portfolio, collecting relevant astronomical material, which could include articles and reading material given by the teacher, own collected reading material, own collected observational material, own written material and any other products of thew course.

These are the formal plans, but real life is not always ideal, which is why I have also made a couple of surveys for middle and high school teacher and a few informal interviews with high school teachers, to get a more realistic understanding of the teaching situation and shed some light on the actual challenges in teaching astronomy in middle and high school. I have used a bottom up analysis to recognize patterns in the responses and get an overall idea of the situation. The results will be covered in the following section.

2.2 Teacher reported challenges

I have asked teachers in the middle school and high school to answer a few questions about their teaching astronomy practice, their challenges and successes. Some of the questions were demographic to establish which levels and subject the teacher was teaching, some where about the practice such as excursions with astronomical relevance and interdisciplinary work, but the most useful questions were about the experienced challenges in the teaching. Below are some key- ndings from the survey.

Challenges in middle school

This survey[2] was shared in a Facebook group[3] for middle school science teachers. A total of 55 teachers replied. As bottom-up analysis of the survey showed that the challenges the teachers experienced fell into a few categories:

1. Teaching material:
   (a) Not enough teaching material
   (b) No practical exercises for this level
   (c) Practical exercises not possible in daytime/teaching time
2. Complexity:
   (a) Subject too abstract
   (b) Subject too big/not enough time
3. The why: Why is astronomy important / how to relate it to everyday life

[2] https://forms.gle/fxqcqiGSBrGe7RYx8
[3] https://www.facebook.com/groups/915402905185143/permalink/3365931250132284

Challenges in high school

This survey[4] was shared in a closed Facebook group[5] for physics high school teachers. 15 high teachers replied. There seemed to be a similar pattern of challenges:

1. Observations are hard or impossible, because weather cannot be planned and due to lack of darkness.

2. Complexity:

   (a) It quickly becomes more complicated, even though it seems easy on the surface.

   (b) The students lack mathematical skills

   (c) The more abstract subjects tend to be more explanatory and memorization, instead of based on physical explanations and calculations.

To get more information on high school teacher's experience with the curriculum, teaching practices, teaching material and any other comments d, I also made few informal semi-structured interviews, with teachers found through my network. One of the ndings from these interviews was that astronomy was not a popular choice in high school (STX) and most classes only had a few students. Some years there were not enough students for the course to be created. One teacher mentioned, that she also often got the question 'why should we learn about this?", which reinforces the idea that it is not easy to see the usefulness of astronomy.

In one interview, one teacher mentioned, that some students chose the optional subject Astronomy because they expected it to be "an easy course". This might at rst glance not sound encouraging, but perhaps such mechanisms could be exploited to use astronomy as a fun entrance to physics or other subjects based on natural curiosity, especially if the 'why" was covered as well, so that the students could see the relevance and "big picture" context.

2.3 Why teach astronomy?

> Astronomy is useful because it raises us above ourselves; it is useful because it is grand; . . . . It shows us how small is man's body, how great his mind, since his intelligence can embrace the whole of this dazzling immensity, where his body is only an obscure point, and enjoy its silent harmony[1] p. 84.
> | Henri Poincare, Physicist

It might be hard to nd a reason for why observing far-away celestial objects or learning about the expansion of the Universe would be useful in everyday life. Beneath the surface, there lies deeper questions in astronomical research: Where did we come from, are we alone in the Universe, what is reality really? These are existential questions asked by humans since our very beginning. In my preliminary survey, teachers in middle school and high school have asked: "How can we make astronomy useful?"

[4] https://forms.gle/VsnJbvVvNPtMy75U7
[5] https://www.facebook.com/groups/fysiklaerer.i.gymnasiet

and "How can it be connected to real life problems?"

Astronomy might be the perfect interdisciplinary subject, that brings cultures together, and inspires arts through its beauty and magni cence. A lot of great arguments are given in the paper [2], which I have collected and grouped below. This will hopefully serve as inspiration for placing astronomy in a larger context.

An interdisciplinary subject

Astronomy is one of the most cross-disciplinary subjects. It can be connected to most other natural sciences such as biology in the search for life and our origins, geology when considering Earth as a planet, chemistry as the elements originate in cosmological events, math and physics for obvious reasons, and humanities such as history, arts, religion, and philosophy.

Sciences

- Physics: Astronomy can be used to illustrate many concepts of physics, such as gravity, light, and light spectra.
- Mathematics: Historically, there has been a lot of mathematical development through astronomy, such as trigonometry, logarithms, and calculus, and hence astronomy can be used to illustrate those branches in mathematics.
- Geology: Astronomy has advanced the geological sciences by providing a variety of environments of other planets and moons.

Humanities

- History: In scienti c revolutions, astronomy stands out. Astronomy has historically contributed to many practical applications.
- Philosophy: Astronomy reveals our cosmic root and place in space and times. It asks the most fundamental questions: What is the origin of the universe, galaxies, stars, planets, atoms, the molecules of life, what is the origin of us and life itself, and are we alone in the Universe?

Technology and applications

The interest and practice of astronomy have led to various kinds of discoveries and technological advancements.

- Timekeeping: One of the most important historical practical applications is timekeeping: Calendars, days, seasons, and years originate from the orbital movement and rotation of Earth around the Sun, and it should be part of general education to know about.
- Navigation: Astronomy has contributed to the development of the GPS and other satellite navigation systems. Einsteins relativity theory has made it possible to make exact corrections to the measurements.

- Natural phenomena: Astronomy explains tides and impacts of asteroids and comets with the Earth.
- Detectors and imaging: Astronomy has led to technological advances in low noise radio receivers and detectors for photography and electronic cameras. The image processing techniques for astronomy are also used in medicine.
- Computers: Astronomers use a large fraction of all the supercomputers in the world, driving the need for further development forward.

Bringing people together

Astronomy not only brings di erent subjects together but also di erent people across time, cultures, and borders.

- International: Astronomical observations require data from di erent latitudes and longitudes and thus foster international co-operation.
- Generations: Some observations require decades and centuries of time, thus linking generations of di erent times.
- Culture: Astronomy is deeply rooted in our culture because of its philosophical implications, and due to the time scales of observations, it also links cultures of di erent times.

Developing di erent kinds of thinking and attitudes

> When I think of science and scientists I think of kids who never lost their curiosity and wonder[6]
> | Neil deGrasse Tyson

- Curiosity: Astronomy harnesses our curiosity, imagination, and exploration. We have gone to the Moon and back, always pushing our geographical limits, ready to explore further in the Solar system.
- Abstract thinking: Due to the enormous distances and time scales, astronomy is great at training the sense of thinking more abstractly about scales of time, distance, and size.
- Rational thinking: If taught properly, astronomy can promote rational thinking and understanding the nature of science through observations and simulations.
- Environmental awareness: Astronomy explains and demonstrates long-term changes in the weather and the e ect of solar radiation. Also, seeing our planet in a greater context from space can make us realize how special and fragile our planet is.

[6] https://thriveglobal.com/stories/neil-degrasse-tyson-on-the-power-of-curiosity/

Beauty and art

> Astronomy reveals a Universe which is vast, varied, and beautiful | the beauty of the night sky, the spectacle of an ecplipse, the excitement of a black hole.[2]
> - John R. Percy

Astronomy has not only scienti c value, but emotional, aesthetic, and artistic values, inspiring artists, poets, stories, and movies. It can be the perfect combination of science and creativity.

The usefulness of astronomy is easier to see in a bigger and long-term context, while the usefulness of our education is often based on more short-term results. This can make it harder to see the context for astronomy, while on the other hand, it is important to keep on eye on the long term goals of developing human society. Astronomy can be abstract and not easy to teach or understand, because it deals with enormous scales and unfamiliar concepts. On the other hand, its strength is that is can be fun, inspiring and curiosity-driven. While it might take more e ort to change the views to long-term goals and bigger picture, it might be easier to sneak the knowledge in disguised as curious fun. Therefore, curiosity-driven learning will be a big part of my thesis.

2.4 Summary of domain research

Regarding the successes that teachers had with teaching: Children and students of all ages nd the topic exciting, so a lot of teachers nd that that astronomy is "easy to teach", in the sense that the students are curious and motivated to learn about the subjects. This is also supported by the study on reasons for teaching astronomy: it helps developing curiosity, creativity and abstract thinking.

It seems to be consistent through the astronomy teaching path in our educational system, that the subjects seems to be exciting, but quickly turns hard to understand and complex to teach, if we go beyond the explanatory and focus on the physics behind. The right balance need to be found. It is also a problem, that most observational astronomy is best done in darkness and even for the experiments that can be done in daytime, the weather conditions are unpredictable.

Some of the challenges depend on which level we choose to focus on. The lack of useful teaching material seemed to be mostly a problem for middle school teachers, although the observational di culties for astronomy follows though all levels. For high school level, the problems seems to lie mostly in the complexity, lack of mathematical skills, and the seemingly easy subject on the surface, which is often solved more by memorization and description than actual problem-solving through the use of physics.

A challenge for high school lies in how to combine something that is exciting, but at the same time makes student use physics and critical thinking for solving the problems.

Part II

Case: Exoplanet Design

In this part, I will present the case that I will be working on and testing in the thesis. As mentioned, I have chosen to focus on exoplanets and the search for life in the Universe. This is still a broad topic with many aspects, which I will narrow down eventually for the case of teaching material. My focus is on the physics and hence more on observing exoplanets and deriving properties rather than the biology behind possible life that could exist on such planets, but one almost cannot consider exoplanets without considering either the possibility of finding new life or the conditions that would be habitable for biological life as we know it on Earth. This is the context that makes the object that are light-years away from us relevant.

I have based my teaching material on an existing package called "Exoplanet Design" (appendix C), which was originally made by as a creative exercise for elementary school children by Faulkes Telescopes[7] for the Online Observatory (OO). I translated the package to Danish and planned to use this as test material for both middle school, and thereafter make appropriate changes, to develop it into a high school level. Unfortunately, I never got to test with the middle school due to COVID-19 lock-down at the day of the test.

This part of the thesis will be in two sections:

- The physics of exoplanets, where I will lay out all the physics which can be used to derive a planetary properties such as their mass and size, atmosphere, temperature. I will also discuss other relevant properties to know, that we cannot quite derive from the current observations.
- The "Exoplanet design" package, where I will narrow the various discussed physics in the previous section to a relevant level for high school students and put together to a teaching material package.

Hence, in the following section, I will explore the rich body of physics information that can be useful for working with exoplanets with students on a high school level, and thereafter narrow it down and prioritize for the specific case.

[7] http://www.faulkes-telescope.com/

3 The physics of exoplanets

To variety of exoplanets and their possible environments has continuously surprised us since the first discovery in 1995[3]. The methods and instruments for exoplanet observations are still being refined, and so far we have many interesting candidates for possible extraterrstrial life, but we have yet to be able to observe with enough resolution to derive implications about the planetary composition and atmosphere, especially when dealing with rocky planets. Those relatively tiny celestial objects are completely outshined by their nearby host stars, and any potential atmosphere of rocky bodies do not have enough height for current technology to resolve.

But let me start by a shortly introducing the package "Exoplanet Design" for middle school (appendix C), which inspired the subject here and a further development of teaching material for high school level. Since the target audience for this teaching material are young children, the focus is more on raising the awareness of the idea of planets outside the solar system rather than a detailed knowledge on derivation of their properties. Since the middle school students are just learning about the Earth, the Moon and the planets in the solar system and simple understanding of the models (section 2.1.1), eventual physics should be included as simple analogies based upon current knowledge of our solar system. Choosing an angle that will be based on their natural curiosity, the main focus on this teaching material for this age group is to see our planet and the planets in our Solar system as part of a bigger context and then use this as a creative exercise of considering the possibilities.

Upping up the game to high school level, an exercise of designing an exoplanet would can be expanded for students to include the use of physics equations. Designing an exoplanet with realistic values requires us to know about exoplanets. I wanted to develop teaching material based on physics, but also find the right level and balance between interesting information that is not too complex to implement. Therefore, I have explored the rich body of information we can observe and derive with some uncertainties about exoplanet, and the methods used for finding and deriving the information. This is what I present in this section, before narrowing the information down to an implementation for use in the test and analysis.

Our knowledge is based upon observations with our senses (mainly our vision) and technologies that can extend our observational abilities. The methods and uncertainty of observing will have an influence on the observable parameters. Therefore, I have split this section will be in three parts:

1. A description of methods used for discovery and observation of exoplanets, and which parameters it is possible to derivable from these methods
2. How we use physics and equations to derive the above mentioned parameters
3. Other considerations about exoplanets, not yet possible to measure or derive, but still relevant for the conditions of an exoplanet and its habitability

3.1 Discovering and observing exoplanets

Since the first confirmed discovery in 1995, over 4000 exoplanets have officially been discovered and confirmed[8], and there are thousands more candidates, which means planets that are likely to have been discovered by one instrument, but still needs to be verified by another.

There are different ways of discovering an exoplanet, but two main methods stand out: The transit method and the radial velocity. The radial velocity was the first method used for exoplanet discovery. In the period 2009-2018, the Kepler mission discovered more than 2000 confirmed exoplanets with the transit method.

Figure 1: Planets discovered with different discovery methods. The transit methods mainly finds planets that are close to their host star ($\lesssim 1$AU), radial velocity discovered planets are also fairly close to their star ($\lesssim 10$AU) and typically with a higher mass. The microlensing and imagining methods both discover planets that are in the outskirts of their solar system, and specifically imagining needs massive planets with a higher luminosity. Data and graph by exoplanet.org, own markings of discovery methods.

3.1.1 The transit method

When a planet transits its host star from our point of view, it blocks a fraction of the stellar light. If the star-planet system is observed over a period of time and the flux is measured, then a periodical dip in the light curve will indicate something passing in front of it, and hence must be in orbit around the star. If its periodical and sufficiently small, it is most likely a planet. A visual explanation of this effect is shown in figure

[8] https://exoplanets.nasa.gov/

2.

Figure 2: Transit light curves for Kepler's first five exoplanets. The depth of the curve depends on the planet-star radius ratio while the width of the curve depends on the star radius and the planet to star distance (a shorter distance will give a faster transit) and the angle we have on the orbital plane (the larger the angle is from 0, the faster the transit). Image source: NASA, https://www.nasa.gov/mission_pages/kepler/multimedia/images/aas_conference.html

This dip is incredible small for transiting planets. As the scale in the figure indicates, the planet blocks less than 1% of the light from the star. What is not shown in the figure, is that the flux also varies when the planet is not in transit. This is due to the fact, that the light we measure is not only from the star, but also light that is reflected from the star by the planet. When in transit, we see the night side of the planet and hence total flux is at its absolute lowest. We should measure the highest value of the flux just before the eclipse of the planet behind the star. In the moments before, we see the full star flux and the full reflection of the day side of the planet. This can be seen in figure 3a.

The occultation depth is the flux difference between the star alone, when the planet is in occultation behind the star, and the star plus planet dayside as seen in figure 3a (A). By comparing the light spectra from the host star and the planet, we might find indications of the composition of the planetary atmosphere. More about that in the spectroscopy-section 3.1.5.

We might also compare the flux from the day side and the night side by comparing A and B. Large differences could imply a tidally locked planet, where the day-side is always facing the star and the night-side always away. Small difference could mean that the planet is rotating quicker and hence have "days" as Earth. Another important factor that could influence the day-night side difference in flux is the atmospheric circulation, which depend on the atmospheric composition and pressure variations. In the case where the flux from the star plus planet night-side (B) is roughly the same as the light from the star alone (occultation), this might suggest that there is no atmospheric circulation and that the planet is tidally locked to its host star.

(a) The measured ux for di erent positions of the planet compared to it is host star. The ux is highest for the visible part of the planets dayside since the re ected light is maximized here (A). The ux is lowest when the planet transits. The ux di erence between just before and during the occultation, is called the occultation depth and gives us the day-time ux from the planet alone, which can be used to analyze planetary atmosphere composition. Image Source: Transits and Occultations[4]

(b) A full-phase 4.5 m light curve of the hot jupiter HD 209458b. Point A shows the highest ux rate from star + dayside of the planet. Point B shows the ux of star planet nightside. The A-B di erence is the di erence in the re ected ux in day- vs. nightside, and in this case it is predicted to be in synchronous rotation (tidally locked). Image source: Robert Zellem, CIT[5]

Figure 3: Transit method

The time between each transits or occultations is the orbital period of the planet. The orbital distance can then be derived from Kepler's third law:

$$P^2 = \frac{4^2}{GM\ m_p}\ a^3)\quad a^3 = P^2\ \frac{G(M\ +\ m_p)}{4^2} \tag{1}$$

Using relative values of M in solar masses, and assuming the mass of the planet can be neglected in the mass of the star-planet system, we can nd the relative orbital distance, a, in AU:

$$a^3 = P^2 M \tag{2}$$

We can calculate an estimated radius from the transit method and directly measure the orbital period.

The transit depth of the curve, as seen in gure 2, gives us an indication of the star to planet size ratio. It is given by:

$$d = \frac{R_p}{R}^2)\quad R_p = R\ \sqrt{d} \tag{3}$$

The exact radius of the planet would also depend on the orbital inclination, which we will de ne as the "impact parameter", as seen in gure 4.
The impact parameter is de ned as:

$$b = \frac{a\cos i}{R} \tag{4}$$

Figure 4: The impact parameter, b, is the one-dimensional sky projected distance from the center of the star to the center of the planet at conjuction.

b can vary from b=0 (the inclination of the planetary orbit is perpendicular to the sky projection) to b=1 (planet passes at the outer border of the star. Since the star is too far away to actually see the transit visually, we cannot know the impact parameter from the transit measurements alone and we will have great uncertainty on the radius calculations.

It is important to remember, that only planets with an orbital plane resulting in 0 b 1, can be discovered with the transit method. Since all planets in a planetary system being born from the same protoplanetary disk have roughly the same inclination, we will miss all planets orbiting a star, if the orbital plane is perpendicular to our line of sight. Also, it is easier to discover larger planets, or at least larger planet to star size ratio, nearer their host star, because this is where most light will be blocked by the planet.

So, to summarise, the information that we can get om the planet from a transit light curves are:

- Orbital period ('year'), directly read from the ux plot
- Orbital distance, derived from period and Kepler's third law
- Radius - derived from star radius and the transit depth
- An idea about atmosphere composition if combined with spectroscopy (section 3.1.5)
- Rough indication of possible atmospheric circulations
- Rough indication on planet rotation ('day')

Only planets with an orbital inclinations towards our line of sight will be able to be observed, and the chances of discovering the planet are roughly proportional to their planet/star radius ratio (transit depth) and inverse proportional with the distance from the host star, a, and impact parameter, b. Therefore, the observation method might be biased towards nding larger planets orbiting closer around proportionally smaller stars.

3.1.2 Radial velocity

A planet orbiting a star is part of a (at least) two body system, where the bodies are revolving around a common center of mass. This means that it is not only the planet that's moving, but also the star. The center of mass of two objects is de ned as $m_1 a_1 = m_2 a_2$, where m_1 and m_2 are the two masses and a_1 and a_2 are the distances to the center of mass for each object. If a is the total distance between the bodies ($a_1 + a_2$), revolving around each other, the equation can be rewritten to

$$a_2 = \frac{m_1}{m_1 + m_2} \, a \tag{5}$$

If the star has mass m_1 then a_2 is the distance from the planet to the center of mass. The star being in the order of hundreds or thousands times more massive, the fraction goes toward 1 and the distance to the center of mass is almost the same as the distance to the center of the star. But not exactly. The small distance from the center of the star, means that the star is 'wobbling" a bit round a center of mass either inside of it or a bit outside. It also means, that it will move slightly back and forth in our line of sight, making it possible to detect slight Doppler shifts in the wavelengths, from when it moves toward or away from us.

The measurement of the Doppler e ect will result in a sine curve. The orbital period of the star itself is easily extracted directly from the measurement, since this will be the period of time where the movement pattern repeats (the wavelength of the sine curve in gure 5).

Figure 5: Radial velocity as a function of time. Image source: Cosmogoblin, Wikimedia commons

From radial velocity observation we can derive the mass of the planet. There are three steps involved. First, we use Kepler's third law to nd the orbital distance of the planet:

$$a^3 = P^2 M \, \frac{G}{4^2} \tag{6}$$

The orbital period of the star is the period of time that we can read from measurements.

Second, we derive the velocity of the planet from Newton's law of gravity which equals the centrifugal force on the planet, where we assume a circular orbit[9]

$$F_g = G\frac{M\ m_p}{a^2} \quad ; \quad F_c = \frac{m_p v_p^2}{a^2}) \quad \frac{GM\ m_p}{a^2} = \frac{m_p v_p^2}{a^2}) \quad v_p = \sqrt{\frac{GM}{}} \tag{7}$$

Third, we find the mass by using the conservation of momentum for the two bodies in the system:

$$M\ v\ = M_p v_p) \quad m_p = \frac{M\ v}{v_p} = \frac{M\ v}{v_p} \tag{8}$$

The velocity of the star can be found from the Doppler shifts in the light spectrum, $v = \frac{}{_{rest}}c$.

This is the minimum estimate of the mass of the planet, because we only measure the velocity in the line if sight. If the orbit is inclined from our line of sight, then the true wobbling velocity of the star will be higher than the one we have measured, and hence the resulting true mass of the planet will be higher.[10]

If we want to calculate the true mass, we need to know the inclination angle i (as also seen and mentioned in transit section 3.1.1):

$$m_{p;true} = \frac{m_{p;min}}{\sin i} \tag{9}$$

There are many ways an orbit can be inclined from our sight of view. Not only can the orbit be inclined relative to our view, but it can also be inclined relative to the stellar axis of rotation. Such inclination can be implied by a Rossiter-McLaughlin effect[6], which is due to the fact, that the light from the star will be blueshifted on the side that rotates towards us and redshifted on the side that rotates away. This means, that the light curves will differ in spin-orbit alignment depending on the fraction of light that is blocked on either side of the star compared to is rotational axis.

Radial velocity is the method that has been used to discover most planets next to the transit method. Those two methods are also complimentary because one can find the radius and the other the mass of the planet. Both methods are best suited for big planets with high mass or radius and for planets orbiting close to their host star. The radial velocity is even more sensitive to the orbital distance than the transit method.

So, to summarise, these are the exoplanet properties, that can be determined from the radial velocity method:

- Orbital period
- Minimum mass
- An indication of the orbit inclination relative to the stellar axis of rotation

[9] Which might not be entirely correct, so the measured velocity might not be completely accurate for the whole orbit

[10] Note that the velocity of the planet will also be higher, but due to same momentum of star and planet and the hundreds or thousand time higher mass of the star, the error in the velocity of the planet will be a few orders less than the error in the star velocity

3.1.3 Gravitational microlensing

Observation of a star and exoplanet with gravitational microlensing, also called a binary-source event, is a one-time experience with the invloved objects. It occurs when the host star of a planet is passing in front of another bright star further away. The gravitational elds of the host star will bend the light of the background star and while it is passing directly in front, it will intensify it like a magnifying glass.

If the host star has a planet orbiting, the planet will also have a smaller impact on the light with it is its turn to pass directly in front. This required of course that the planet is not in transit or occultation while the system microlenses the background light (See gure 6). Microlensing is hard to measure, both because of it is one-time lucky coincidence, but also because of the time frame. If the timeframe for a star microlensing the background light is around a month, then the time for the e ect of the planet will be only a few hours.

Figure 6: Exoplanet detection by gravitational microlensing. Image credits: NASA, ESA, and K. Sahu (STScI),https://exoplanets.nasa.gov/resources/53/extrasolar-planet-detected-by-gravitational-microlensing/

It might be a useful method for con rming exoplanets found through another method, in case the host star is in a lucky position to another background light. Also we might be able to estimate the mass ratio of the planet to the star and the planets orbital distance. This is done by comparison of the data to theoretical models. Since the mass is important for the gravitational e ect, the more massive stars are easier to detect with this method.

Also, planets that orbit in large distance from their star, are also easier to discover, because the magni cation of the light will be easier to distinguish from the magni cation e ect by the host star. The inclination of the planetary disk does not matter in this

method, and hence it is possible to detect planet candidates that would not be possible to discover through transit or radial velocity due to an inclination perpendicular to the sky projection.

3.1.4 Direct imaging and other methods

Direct imaging is also an option, alas for now only possible for large gas-planets in large orbital distance. This methods requires a large telescope with adaptive optic system and high angular resolution. Still, only planets that orbit in a large distance from their host star can be visually captured in an image. If the planet is too close, the star will outshine it a billion times in the optical part of the spectrum.

Direct imaging and gravitational microlensing is complimentary to both the transit and radial velocity method. While the latter are best suited for large planets near the host star, the imaging and microlensing method can be used to detect large bodies in the outskirts of a solar system.

3.1.5 Spectroscopy

Once a planet is discovered and con rmed, we can collect light curves from di erent positions of the exoplanet as seen in gure 3a, from the occultation, the transit or from a planet position in between. In the occultation position, we get ux from the star only. In transit we get ux from the star and thermal emission from the planet, minus the light blocked by the planet. In between we get ux from the star and the re ected ux and thermal emission from the visible part of the planet.

One way of collecting spectra data from the planet is by transmission spectroscopy. In transmission spectroscopy, we measure the ux from the star-planet-system, while the star is in transit and compare with the ux from the star itself when the planet is in occultation. By subtracting the stellar ux from the total star-planet ux when the planet is in transit we obtain a planet spectrum. Some of the stellar light will also pass through the upper levels of the atmosphere (if an atmosphere exists) of the exoplanet, probing it through a range of optical depths.

It is incredibly di cult to get detailed spectra of exoplanets atmosphere due to the tiny fraction of the light from the star that passes through a planet's atmosphere, because the atmospheric layer is very thin. We are able to obtain low resolution spectra with a few speci c points for Hot Jupiters, where the atmosphere could be several hundreds of km, while we still have to wait for a better telescope, such as the long awaited James Webb Space Telescope (JWST[11]), which hopefully will be launched in 2021, to be able to study Earth-like and super-Earth planet atmospheres. Earth has a an atmosphere with a height of about 8 km.

3.2 Derivable exoplanet parameters

It is our eyes that look through the telescopes when we observe, but it is the brain that sees and our mind that interprets and draws conclusions. Our detectors, eyes

[11] https://www.jwst.nasa.gov/

or build in telescopes, receive electromagnetic signals, and our brain interprets the incoming signals based on both intuitive neurological processes as a result of our biological adaption to our experience living on planet Earth, while others are developed through science and the rational mind. From our assumptions of fundamental principles of space and time, we derive and draw conclusions about distances, periodical time, shapes and sizes with more or less certainty. What we think we know depends on those assumptions being true.

In the case of teaching exoplanets in high school, I would like to be able to include calculations that the students will be able to do to derive realistic values based on physical principles that they have been taught, balancing a creative imagination in the exoplanet design. In this section I will therefore focus on the derivable parameters, that I nd relevant for the teaching package, based on what is possible to observe, as described in previous section 3.1. Which parameters I choose for the case in the end and why, will be described in the following section 4.

3.2.1 Orbital period and radius

The orbital period of the planet can be derived directly from both the transit and radial velocity method as described in the respective sections 3.1.1 and 3.1.2. The orbital distance (or separation) is derived using Kepler's third law, which is taught in high school in both rst year physics and the astronomy elective course.

Kepler's third law in the general form using standard units in eq. 6, can be simpli ed by using star mass in sun-masses and orbital period in earth years, resulting in a relative orbital distance in AU:

$$\frac{a^3}{[1\mathrm{AU}]} = \frac{T^2}{[1\mathrm{Year}]}\frac{M}{[1M_{\mathrm{sun}}]} \quad) \quad a^3[\mathrm{AU}] = T^2 M \tag{10}$$

3.2.2 Mass, size, surface gravity and density

As we saw in the method section, a minimum mass can be derived from the radial velocity method (eq. 8 and eq. 9) while size can be derived from the transit method (eq. 3). Both the density and the surface gravity of the planet can be derived when the mass and radius are known, e.g. when combining observation with transit and radial velocity method.

Using Newtons law of gravitation $F_g = Gmm_p/R_p^2 = mg$, where m is the mass of an object on the surface of the planet of mass M_p and radius R_p and g is the gravitational acceleration at the surface, given in units $[N/kg] = [m/s^2]$, the mass of the object cancels out, resulting in:

$$g = \frac{M_p G}{R_p^2} \tag{11}$$

The surface gravity of a planet can have an e ect on the atmosphere. If the surface gravity is small, such as the case with Mars, which has a surface gravity of about 1/3 of Earth, it will have a harder time holding on to a volatile atmosphere. Note: When dealing with gas giants, we de ne the radius as the total radius at which stellar light is absorbed from the planet and hence the surface is de ned as the top layer of the

atmosphere.

The density of the planet is important for learning about the planet's physical structure and is found by dividing the found measured with the volume $V = \frac{4}{3} R^3$:

$$= \frac{m}{V} = \frac{4\,m}{3R^3} \tag{12}$$

3.2.3 Elements in the atmosphere

By observing and comparing spectra of the host star and the planet, we might detect di erent elements in the planetary atmosphere. Due to the di erences in atomic and molecular structure, di erent atoms, ions, and molecules absorb light from the host star at di erent wavelenghts, and hence there will be absorption lines in the transit spectrum, that cannot be seen in spectra from the star alone.

As already mentioned in section 3.1.5, it is di cult to obtain high enough resolution spectra for the planet atmosphere due to the massive amounts of ux coming from the star relative to the planet. For Hot Jupiters, where the planet has a larger amount of atmosphere close to the radiation, this can be done with current telescopes, but for smaller rocky planets, we need better tools.

Flux from a star can exceed the ux from a hot Jupiter by for example six orders of magnitude or more (gure 7), which makes measurement of the relative uxes di cult. In longer infrared wavelength this di erence in ux becomes smaller and measurements measurements can be more precise. The ux di erence between a Sun-like star and an Earth-size planet will even in the infrared measurements be at least seven magnitudes. The above mentioned JWST will among other improvements have a larger angular resolution and longer wavelength coverage making it possible to create spectra of rocky planets atmospheres.

When observing atmospheres, it is especially interesting to look for biomarkers, which are elements that should not be found in an atmospheric equilibrium, which then could indicate something, that shifts the equilibrium, such s life or geological activities. For example, a combination of ndingO_2 or O_3 with CH_4 would indicate an atmospheric disequilibrium, since this elements would naturally react into water and carbon dioxide. In the calculations, a planet is assumed in thermodynamic equilibrium. This is not necessarily the case, for example if the planet contains life.

3.2.4 Planet temperature

The temperature of a planet cannot be derived directly from our observation methods, but is one of the most important factors for whether a planet is habitable or not. We de ne the equilibrium temperature as the temperature at which absorbed power of the planet equals radiated power from the planet. We can use the equilibrium temperature as the starting point for the average temperature of a planet.

There are other factors that will in uence the true temperature of the planet, such as the greenhouse e ect (section 3.3.3) for the overall averages and the tilt (3.3.4)

Figure 7: Approximations of star-planet distribution of re ected and emitted ux for planet-star ux ratio of a sun-like star, a hot jupiter and our solar system planets (Jupiter, Venus, Earth and Mars) [7]

and eccentricity (3.3.5) for local variations. For comparison, the calculated e ective temperature of Earth would be 252 K (-21C). The true average global temperature of Earth is 288 K (15 C). The greenhouse e ects of some gasses in the atmosphere can increases the true surface temperature substantially.

The temperature also depends on the (bond) albedo[8] - the fraction of received light re ected by the planet surface. The albedo depends on the surface material of the planet, which again depends on the components that the planet consist of. This will be described in one of the following sections, 3.3.1.

Starting with the equations for absorbed power from the star and radiated power from the planet interior, and using the equation for the luminosity of a black body, $L = 4 R^2 T^4$, we can derive the equilibrium temperature:

$$
\begin{aligned}
P_{abs} &= P_{rad} \\
\underbrace{\frac{L}{4a^2}}_{\text{Absorbed fraction}} \underbrace{R_p^2 (1 - A_B)}_{\text{Surface Area}} &= \underbrace{4 R_p^2 T_{eq}^4}_{\text{Flux}} \\
T_{eq} &= \left(\frac{L}{16 a^2} (1 - A_B) \right)^{1/4} \\
T_{eq} &= T (1 - A_B)^{1/4} \sqrt{R_s / 2a}
\end{aligned}
\tag{13}
$$

Hence, we can derive the equilibrium temperature of a planet from the radius and temperature of the host star, the orbital distance and the bond albedo. For $A_B = 0$

all the energy gets absorbed while $A = 1$ means all the energy gets re ected. A planet with re ection albedo of zero will absorb the highest amount of energy, appearing darker and have the highest temperature for its parameters.

In this we assume that the planet does not have any intrinsic energy source in it self. While this might be negligible for ordinary rocky planets, it might not be for large-sized gaseous planets. The total e ective temperature is then the sum of the radiation equilibrium temperature and the intrinsic temperature:

$$T_e = T_{eq} + T_{int} \tag{14}$$

3.3 Other considerations for exoplanets

In this section, I will go through a few physical parameters, that are relevant to know about a planet, but that are not as easy to derive from the observables.

3.3.1 Albedo

As mentioned in the previous section, the albedo is a measure of the planet's ability to re ect light from the star. The re ectivity is the ratio of scattered light from the light received by the planet. There are di erent ways to de ne the albedo. Bond Albedo (A_B) is the ratio of total re ected stellar power to the total power radiated on the planet. This is the ratio that we use for calculation of the equilibrium temperature (section 3.2.4).

Bond albedo, which is used in determining the planetary equilibrium temperature, depends on the spectrum of the incident light from the host star[12] as well as the planetary surface and atmosphere, which partially can absorb some of the radiation. Since the planetary surface conditions are not easy to estimate, the albedo and hence the equilibrium temperature can only be rough guesstimates for an exoplanet. H_2O-vapor will for example absorb majority of the energy it receives and hence planets with more water molecules in the atmosphere will have a lower albedo and warmer temperatures. Liquid and solid water will on the other hand have a high re ectivity, which means that water or ice on the surface will re ect more light and lower the surface temperature.

3.3.2 Atmospheric pressure

The atmospheric pressure on the planetary surface is a direct result of the amount of atmosphere weighting down on it, hence it varies with the altitude. The pressure at the surface depends on how far up the atmosphere stretches.

The surface pressure will a ect the temperature range at which water can stay liquid, which de nes the planetary habitable zone. Therefore, we need to take the pressure into account, when considering the habitability of a planet. As seen in gure 8, the temperature range is ideally not enough to state whether can have liquid water. On a planet with low pressure such as Mars, there surface pressure is around the triple point and water will go directly from ice to vapor at temperatures around 0C, while

[12] https://www.britannica.com/science/albedo (March 2021)

liquid water could exist on a high pressure planet like Venus, if the temperature was below 350C.

Figure 8: Pressure-Temperature phase diagram for water. Image credits: Bernd Lehmann, TUC, Department of Geology and Paleontology

The gravity of the planet will help holding on to an atmosphere, so the more massive the planet compared to its radius (squared), the higher the chance of being able to keep an atmosphere, especially with light elements with lower escape velocities in the atmosphere. A gas giant will always have a thicker atmosphere as part of it is gaseous whole. It might be harder to de ne the surface on such.

3.3.3 Surface and weather

We can roughly categorize planets in four di erent types: Terrestrial, Super-earths with a loosely de end mass of 1-10 Earth masses, Neptune-like and Gas Giants, which can be up to 4000 Earth masses. A sub-category of the gas giants are the Hot Jupiters, which are Gas Giants that orbit close to their host stars.

The Terrestrial and Super-Earths are rocky planets, which have an easy de ned solid surface and a perhaps a thin layer of atmosphere. The Neptune-like "ice giants" and the gas giants on the other hand, are thought to have a rocky and an interior of a fraction of metallic hydrogen[7]. Neptune-like planets have a layer of melted ices between the outer gas layer and the solid core.

The surface of a gas planet is harder to de ne, since most of the planet composition is gas. One common de nition of the surface is where the pressure is 1 bar. Atmosphere at this altitude will remain fairly uniform in density and temperature because it is deep enough not to be in uenced by external factors, such as solar wind. While the surface of a gas giant or Neptune like planet will be gaseous, the rocky planets can

have both solid and liquid surface.

The atmosphere of a gas giant is thought to originate from direct capture of gas form the protoplanetary disk, while the atmosphere for rocky planets are thought to come from planetary accretion. The atmosphere of a planet depends on both the original source of the gasses and the location of the planet in the protoplanetary disk during formation and on atmospheric escapes. Due to the atmospheric origin in gas giants and to their larger gravity, the atmospheric composition of the gas giants will more likely be unchanged during the solar system evolution, which means that their composition will be similar to the solar composition. This does not apply to rocky type planets.

The atmospheric compositions of exoplanets are still to be uncovered both theoretically and observationaly. When we look at exoplanet spectra (so far primarily for Hot Jupiters), we try to find absorption lines for elements and molecules. In addition to the chemical composition, we also need to take into account that some of the compounds will form clouds, depending on the temperature, pressure and condensation curve for the gasses.

We have a fair understanding of atmospheric compositions of the planets in our solar system. There are a few dominant molecules, such as CH_4, NH_3, H_2O and H_2 in gas giants while the Terrestrial planets are dominated by the CO_2 gas. The composition of Earth is dominated by 78% N_2 and 21% O_2. Only 0.04% of our current atmosphere is CO_2. The lack of CO_2 compared to the other Terrestrial planets in our solar system is due to the disequilibrium created by life. Although only a relative small amounts of gasses such as CO_2 and CH_4, they still have a great impact on our climate, functioning as strongly absorbing greenhouse gasses, unlike the homonuclear diatomic molecules, such as H_2 and O_2.

The atmosphere of a planet, regardless the planet type, can be either clear or cloudy, but most planets with equilibrium temperature less than 2400 K, will have dust, grain or liquid formation in the form of clouds[9], which is easily seen observing our own solar system, where clouds can be found in every planetary atmosphere. Clouds are important because of their contribution to the atmospheric energy balance[7]. Depending on the cloud composition, they might contribute to a higher albedo (such as water clouds), reflecting solar light and cooling down a planet. Other compositions are strong absorbers of short wavelength light. Clouds can change the planetary atmosphere, the temperature and the circulation. It is a whole field of study, which is outside the scope of this thesis, but it is important to note, that they will have a big influence on the planetary atmosphere. From the existence of clouds, one could continue and imagine the precipitation with liquid and solid compounds, both dependent on the components and their phase determined by temperature and pressure.

At last, it might be relevant to mention the importance of atmospheric circulation, which the spectra of dayside versus night side flux of a planet can partially reveal. A smaller temperature difference between day and night than expected (for example in tidally locked planets) might give a hint of large atmospheric circulation. The dynamics of this circulation requires complex and time consuming calculations, which I will not go into here, but in the context of exoplanet design, one could consider winds on

the planet surface and their signi cance for reducing the temperature gradients.

3.3.4 Axial tilt

The tilt of the Earth, which is about 23.5 is what makes up our seasons. But that is not the only importance of the tilt. The tilt of Earth is, unlike the tilt of Mars, very stable. The stability is what makes the seasons predictable and gives life on Earth predictable cycles, which is crucial for the development of advanced life[13]

Here, the Moon also play an important role. The gravitational e ect of our Moon stabilizes the tilt, which might have otherwise have changed under the in uence of the Sun or Jupiter. Likewise the tilt of an exoplanet can have great importance on the possibility of the development of life. This is part of the Rare Earth Hypothesis[10].

One could imagine which e ect another tilt would have on life on the planet. A tilt close to 0 C like Mercury, would have most of its energy distributed at the equator and least on the poles, while the opposite would be the case in a 90 such as Uranus, or of the tilt was unstable because of the lack of a stabilizing moon or a closer distance to a more massive object in the solar system. The main thing here, is that the temperature di erences would be very high in such case, and it would disturb an consistent evolution. Or a stable location for our travel destination, if that was to be the point of the planet.

No measurements can so far give us any indications of an exoplanetary axial tilt, although some observations of planetary resonances or the lack of such, might indicate large planetary axial tilts. This relates to Kozai mechanism[11], which also a ects the eccentricity of the orbit. The e ect is of time scales much larger than the orbital period.

3.3.5 Eccentricity

Just like the tilt of a planet, the eccentricity of the planetary orbit can have in uences on the variations in temperature. Earth has an eccentricity near 0, which means that the orbital is practically spherical, and hence the seasons are only in uenced by the tilt. Mars has a higher eccentricity, which gives it additional seasons.

The eccentricity can be derived from the radial velocity method if we have enough data points for a phase diagram, as seen in gure 9. Depending on the shape of the phases, we can deduce the eccentricity and the viewing angle. Many observed exoplanets have orbits with larger eccentricities than we see in our own solar system.

3.3.6 Other considerations

There are still more considerations for exoplanets. Rotation about own axis is what created the day and night periods on Earth. As living beings we, as many other living organisms, are highly adapted to this inner circadian rythm of our rotating planet.

Planets near the gravitational elds of the star can be tidally locked which means

[13] http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/orbtilt.html (2020-12-11)

Figure 9: Phase diagrams of planets aroundsstars: a) 51 Pegasi with low eccentricity, b) 70 Virginis with and c) 16 Cygni B woth large eccntricity, Image Source: "An Introduction to Astrobiology"[12]

.

that they move (almost) in a synchronous rotation around their host planet. One such example is our inner most planet Mercury, which "day" is slightly longer than a year, because it rotates at the same time that it orbits the Sun. Another example is our Moon, which is tidally locked to Earth. Many discovered exoplanets are far closer to their host planet than Mercury and depending on the mass of their host star, they will most likely be tidally locked. We cannot derive the rotation from current observation methods, but it is interesting to consider if we were to imagine life on a di erent planet.

Magnetic elds around a planet, generated by liquid metals in the outer core, will also have impact on the planet habitability, for example by protecting the planet from solar winds and also by help keeping the atmosphere from escaping the planet surface gravity. Neither Mars or Venus has a magnetic eld, but while Mars has almost no atmosphere, the opposite is the case on Venus. This is an example on how a magnetic eld is not a necessary condition for an atmosphere, although it does help.

The frequency and strength of solar winds generated by the host star, is another parameter to consider, when considering the habitability. One example is our closet neighboring star, Proxima Centauri, which is a red dwarf with a planet orbiting. The planet experiences solar wind pressures that are thousands of times larger than we have on Earth, so although the planet might be in the habitable zone, it does not mean that it is habitable. This is an example of how habitability is not equal to, but a subset of the habitable zone.

3.4 Summary

While this section focused on the many aspects of observing planets and the possible derived properties of exoplanets, the next section will boil it down to a representation to be used in a high school level teaching material. Table 1 sums up the main possible derivations from the mentioned observation methods.

	Transit	RV	Spectroscopy
	Light curve	Velocity curve	Spectrum
Orbital period (year)	X	X	
Orbital Distance	X		
Planet Radius	X		
Atmospheric composition	(X)		X
Atmospheric circulations	(X)		
Planet rotation (day)	(X)		
Planet mass		X	
Orbital inclination / to stellar axis		(X)	
Albedo			
Atmospheric pressure	(X)		
Axial tilt			
Orbital eccentricity	(X)		

Table 1: Possible properties derived from observation methods

4 The package: Exoplanet Design

In the previous section, I presented observations and derivations of exoplanet properties. In this section I will narrow this down to a few equations for high school students to work with. Those should be relevant for properties that are important from an reverse engineering point of view. In real life, we don't "design" exoplanets, we observe and try to model the reality. In the exercise, the students start with an imaginary exoplanet of their choice, and thereafter reverse engineer the properties to make it realistic and pluasible. The purpose of this is to train the students in using physics in a creative and self-determined context.

As mentioned, I have used an existing package called "Exoplanet Design" for elementary school level as a starting point for a similar exercise for high school level. The original exercise is attached in appendix C, and is targeted for middle school students. It consists of student guide, a teacher guide and a presentation like all of the packages for Online Observatory. While the focus in the middle school level was on raising the awareness of diversity of planets outside our solar system and thereafter consider the possible life evolved in alien scenarios, at high school level a signi cant amount of relevant physics can be added to the creative aspects. This is where some of the physics from the previous section can be introduced. Both packages are based on NASA's Exoplanet Travel Bureau[14] for poster inspirations and use NASA's Eye on Exoplanet[15] for information and inspiration on discovered exoplanets and their host stars. I have included the material for the high school package as described in the following in appendix D.

In the presentation for teaching material for exoplanet design, the students are introduced to the relevant background and NASA's resources, and thereafter a walkthrough of various properties for an exoplanet and the methods for calculating those properties if possible. The methods for observing exoplanets are shortly mentioned, but are expected to have been introduced in a previous session. A graphical overview of as seen in gure 10 is included to give a better sense the properties grouped in 4 categories: 1) The host star and its in uence on the planet temperature, 2) The size and gravity of the planet, 3) The planet type, surface and weather, and 4) The "calendar" periods of the planet.

While there could be included many interesting factors to consider when imagining an alien world, time itself is not an unlimited resource for the class lecture and exercise. I wanted to have a balance between the creative parts and the calculations, therefore I chose only a few equations to include. Three of the above categories include calculations, while the surface and weather is mostly a creative exercise without numerical values. I chose a few relevant attributes, that I gured that the students could be expected to calculate, which at the same time were had a big in uence on the design of an exoplanet as a travel destination.

- Equilibrium temperature (with a guesstimate of the albedo)
- Surface gravity

[14] https://exoplanets.nasa.gov/alien-worlds/exoplanet-travel-bureau/
[15] https://exoplanets.nasa.gov/eyes-on-exoplanets/