UNIVERSITY OF AMSTERDAM

LIVING ON A DARK PLANET, ORBITING A BLACK HOLE...

The Wobble

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Abstract

This paper discusses the possible life form on a hypothetical planetary system, consisting of a stellar mass black hole, a moon and an Earth similar planet called the Blanet. The Blanet has an circular orbit around the black hole, while the moon has an precessing elliptical orbit around the Blanet. There is no light source in this system, meaning that the only energy source for the Blanet is tidal heating from the moon. Based on simulations of the environment on the Blanet, we have designed our alien, Wobble, that populates the hydrothermal vents on the Equatorial Ridge at the ocean bottom. The Wobble lives in symbiosis with a thioautotrophic organism. The Wobble is a multicellular organism, consisting of a mother cell that produces smaller differentiated daughter cells. These differentiated cells all have different function so that the Wobble can adapt to the environment. The Wobble has a defence mechanism against unfavourable environments, the quiescence. The Blanet emits infrared radiation and can be detected by the James Webb Space Telescope. By simulation of the population development of the Wobble and its prey, we found chaotic patterns in the CO_2-concentration in the atmosphere of the Blanet, which can be used as bio-signature on the Blanet.

1 Introduction

Earth is home to all life as we know it. So far extraterrestrial life has not been found and perhaps will never be found. But because of the vastness of space and the fact that our species have never managed to go much further than the moon, we optimistically think that life on other planets is highly probable. But if there is life on other planets, what would they look like? How do these organisms function? How are they adapted to the environments on these exoplanets? How did life begin on that planet?

Our goal is to get to know more about what life is, how it emerges and what organisms on different planets could look like. To achieve this, we designed a scientifically plausible alien life form on our own created rocky exoplanet.

Before we began with the creation of our alien, it was important to know what exactly life is. What does it mean to live? What is the definition of life? When you search online, you can find a lot of different definitions. One that often comes up is that something is alive when it is not dead. But then, when is something dead? One quick search later and you find that something is dead when it is not alive. But what is it that differentiates the living from the dead? In this paper we adhere to the following definition of life: “An object is alive when it is able to maintain itself (autonomously) in a state away from equilibrium vis-à-vis continuously inflicted damage that would tend to relax the equilibrium, by repairing that damage or enabling itself to be replaced by undamaged copies” ∼Hans Westerhoff.

Now that we know what life is we have to think of some requirements that all terrestrial life forms should follow. These requirements are summarized in CCEMMM, which stands for containment, catalysis, energy, memory, movement and maintenance. All life forms should have facilities for these concepts. The question is, how does our alien, the Wobble, solve CCEMMM.

Now that we have laid the groundwork for the creation of our extra-terrestrial life form, we have to decide where it would live. To challenge ourselves, we decided to create a hypothetical exoplanet. This resulted in an exoplanet with a moon, orbiting a dormant black hole, otherwise known as a Blanet. This environment is very special and is very different than the environment we are used to. In this system there is no sun to provide energy, so photosynthesis, the mechanism that keeps almost all life on Earth alive, is not an option.

2 Blanetary system

2.1 The Blanet

Our aliens are inhabitants of a hypothetical planet. Instead of orbiting a star like a regular planet, our planet orbits a black hole. This type of planet is called ”Blanet”. [28] The term was first coined by Keiichi Wada from Washeda University. Up till now, no Blanet has been discovered, however, a study in 2018 [21] shows that there could be a safe zone around supermassive black holes which could harbor life. In our study, we will discuss the possibilities with a stellar mass black hole (1200 $M_{\odot}$). We choose our black hole to be a silent black hole, meaning that it does not accrete and does not release high-energetic radiations. Without the presence of an accretion disk, our Blanet is not likely formed around the black hole. Therefore, we hypothesized our Blanet as a rogue Blanet that has been captured by the black hole.
Our Blanet is a rocky planet and has a mass three times the mass of the Earth ($\approx\ 3 \cdot 5.972 \cdot 10^{24}\ kg$) and the same radius as the Earth ($\approx 6.371\ km$). This means that the surface gravity is equal to $29,43 m/s^2$, which is three times the surface gravity on Earth. Assuming the mass of the Blanet’s atmosphere is the same as the Earth’s, the atmospheric pressure will also be three times higher than on Earth ($3 \cdot 101,325\ Pa$). The distance between the Blanet and the black hole is 1 AU.
In this system, there are no other stars of gas giants nearby the Blanet. But the Blanet is not alone. There is a moon that orbits the Blanet in a elliptical orbit, it has a mass equal to 0.05

times the mass of the Earth.

2.2 Orbital dynamics

2.2.1 Characteristics of the Blanet

Our system consists of a black hole, a Blanet and a moon rotating around the Blanet. We will derive the orbital dynamics only considering classical mechanics. The relativistic calculations are for now beyond the scope of this study. We place the Blanet in a circular orbit around the black hole. Let M_{Blanet} be the mass of the Blanet and M_{BH} the mass of the black hole. Let R be the distance between the Blanet and the black hole. According to Kepler's third law, the orbital velocity of the Blanet is

$$\omega = \sqrt{G\frac{M_{Blanet} + M_{BH}}{R^3}} \approx 0.59 \ \ rad/day.$$

The orbital period of the Blanet is given by

$$P = \frac{2\pi}{\omega} \approx 10.55 \ \ days.$$

2.2.2 Characteristics of the moon

For simplicity, we assume the orbits of the black hole, the Blanet and its moon are all in the same plane. The initial distance (for our simulation) between the moon and the Blanet is 0.2 times the distance between the moon and Earth ($\approx 800000 \ \ km$). Since the moon's mass is way smaller compared to the mass of the Blanet and the mass of the black hole, we assume that the moon has no gravitational impact on the Blanet and the black hole. By this assumption, we reduce our system to a circular restricted three-body problem. If we place the origin of our reference frame at the center of mass of the black hole and the Blanet, we can derive the following equations of motion for the moon (see appendix I):

$$\ddot{x} = 2\omega\dot{y} + \omega^2 x - \frac{GM_{BH}(x - x_1)}{p_1^3} - \frac{GM_{Blanet}(x - x_2)}{p_2^3}$$

and

$$\ddot{y} = -2\omega\dot{x} + \omega^2 y - \frac{GM_{BH}(y - y_1)}{p_1^3} - \frac{GM_{Blanet}(y - y_2)}{p_2^3}.$$

These equations of motion are defined in a rotating reference frame. In other words, we rotate ourselves along with the Blanet and the black hole, such that the Blanet and the black hole remain stationary in our reference frame.

2.2.3 Simulation results

We can then simulate the equations above of motion with the parameters given in previous sections. We use the Python-based game engine *Pygame* for the simulation. The code of this project can be found at [7]. Figure 1 shows a screenshot of our simulation. The red dot at the center is the Blanet and the black dot is the moon. The blue and yellow lines define the water level and the height of the tidal bulge of the planet, which we will elaborate on later.
Initially, we placed the moon at $(-80000 \ \ km, 0)$ with respect to the Blanet. The orbits of the moon in 22 days is given by figure 2. (We choose 22 days because it is twice the orbital period of the Blanet around the black hole.) We can see that the moon has elliptical orbits round the Blanet. But the moon is also precessing due to the gravity of the black hole.
We can also plot the distance between the moon and the Blanet with respect to time (figure 3). The periodicity in figure 3 indeed suggests that the moon has elliptical orbits. In every orbit (when the moon goes around the Blanet once), we denote the farthest point to the Blanet as r_a and the closest point to the Blanet as r_p. Because the moon is precessing, different orbits will also have different values for r_a and r_p. The values for r_a and r_p correspond to the (local) maxima and minima of figure 3 respectively. We can find these values by numerical differentiation.

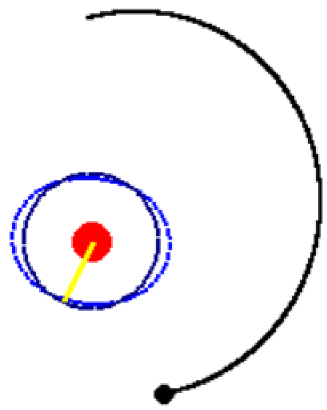

Figure 1: Screenshot of the simulation of our system. The red dot is the Blanet, the black dot the moon. The black hole is not displayed because it is too far away from the Blanet and the moon. Besides, the black hole is a stationary point in our rotating reference frame. Therefore it is not necessary to display it.

Based on the evaluation of our simulation, we obtained the following characteristics of the moon's orbits. $\bar{e}$ stands for the mean eccentricity, and is evaluated by the identity

$$\bar{e} = \frac{\bar{r}_a - \bar{r}_p}{\bar{r}_a + \bar{r}_p}.$$

$\bar{r}_p$ $[m]$	$\bar{r_a}$ $[m]$	$\bar{e}$
41431746.410	83096867.910	0.335

Table 1: Orbital characteristics of the moon. $\bar{r}_p$ is the average closest point to the Blanet and $\bar{r}_a$ the average farthest point to the Blanet.

2.3 Internal Blanet activity and tidal heating

Since we have no star near our Blanet, we will not be able to obtain energy from the radiation of the star. Therefore, the strong tidal interaction present on the Blanet will be the primary source of heating. The tidal heating [33] on the Blanet is given by

$$\dot{E}_{tidal} = -\Im(k_2)\frac{21}{2}\frac{GM_h^2 R^5 n\bar{e}^2}{a^6},$$

where G is the gravitational constant, M_h the mass of the host (in our case either the black hole or the moon), R the radius of the Blanet, n the mean orbital motion (mean angular velocity) and a the mean orbital distance. The main problem to use formula is the $-\Im(k_2)$ term. This is the imaginary component of the second Love number, which measures the efficiency by which the Blanet converts tidal energy into frictional heat. The value of Earth's second love number is between 0.304 and 0.312 [30]. Since we have assumed that the Blanet is Earth-similar, we choose this term to be ≈ 0.3.

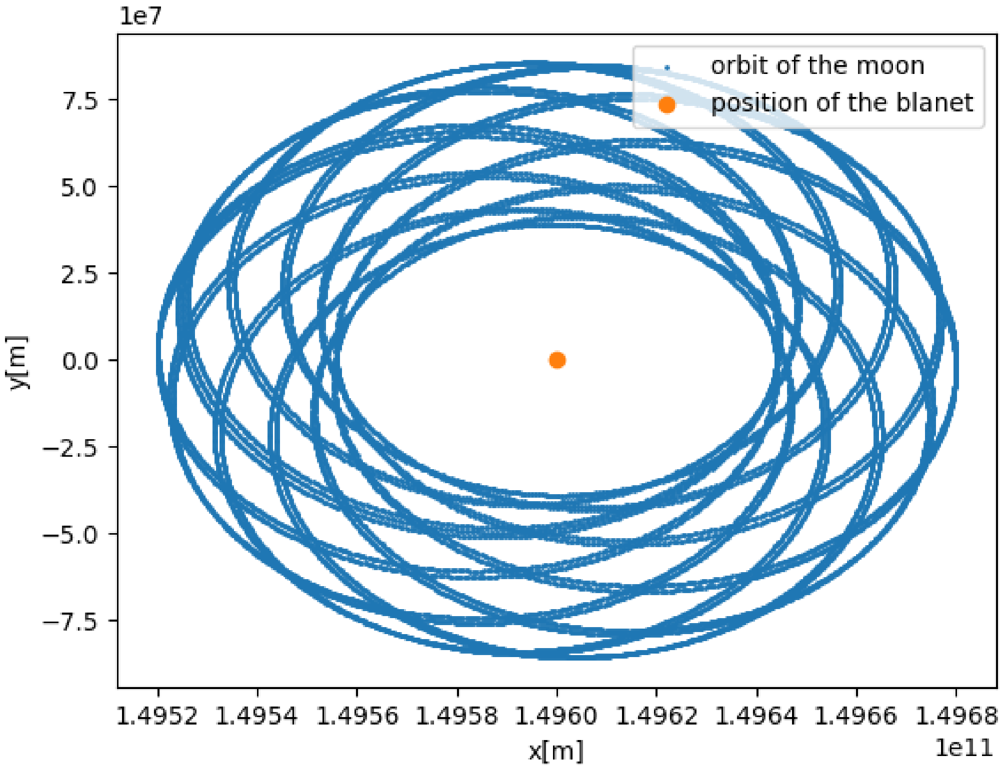

Figure 2: The orbits of the moon in 22 days.

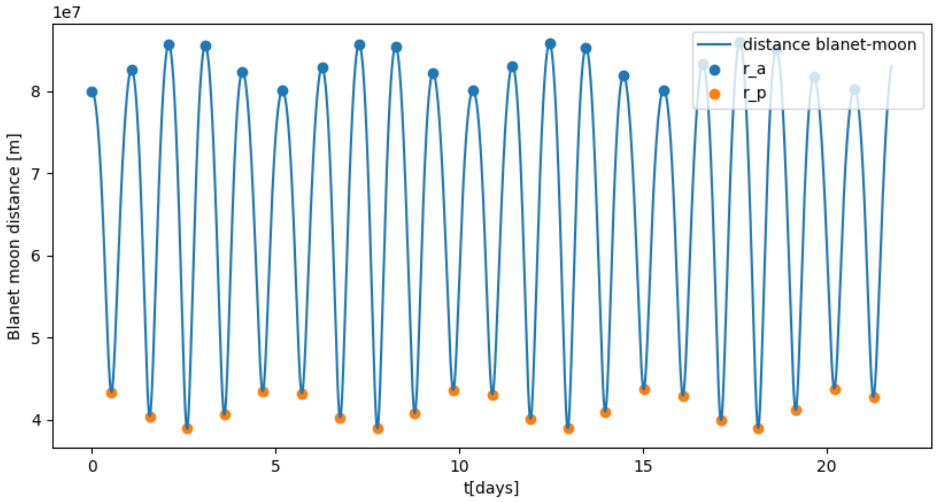

Figure 3: Simulated distance between the Blanet and the moon in 22 days

Based on the above formula, we can see that the black hole does not contribute to the tidal heating Blanet because the Blanet is in circular orbit around the black hole (which means that $e = 0$). Therefore the only tidal heating source is the moon. We have previously calculated the value for $\bar{e}$. The mass of the moon is $0.05 \cdot 5.972 \cdot 10^{24}$ kg and the radius of the Blanet is 6.371 km. The value for both n and a can be directly evaluated by our simulation. Assume that the Blanet is a black body. The equilibrium temperature caused by tidal heating is then given by

$$T_{eq} = \sqrt[4]{\frac{\dot{E}_{tidal}}{4\pi \cdot R^2 \cdot \sigma}},$$

where σ is the Stefan-Boltzmann constant. By putting all the terms together, our simulation yields an equilibrium temperature of $294.657\ K$.
Due to the tidal interaction of our Blanet, we expect large amount of volcanic activities releasing gas and dust particles that will form an atmosphere. We estimate that this atmosphere will absorb 70% of incoming infra-red (heat) radiation. We use the single layer model for the atmosphere. Let P be the input power coming into the atmosphere (due to tidal heating) and P_{out} the output power on one side of the atmosphere. Because the Blanet is assumed to be a black body, the incoming P_{out} to the Blanet, will be 100% re-emitted out of the Blanet towards the atmosphere. Therefore, the total power coming into the atmosphere is

$$P_{in} = P + P_{out}.$$

Let $\alpha = 0.7$ be the absorption rate. The absorbed power will be re-emitted on both sides of the atmosphere with P_{out}. From this, we can derive the following equation

$$\alpha P_{in} = \alpha(P + P_{out}) = 2 \cdot P_{out}.$$

This gives us

$$P_{out} = \frac{\alpha}{2-\alpha} P.$$

We denote P_{out} as the green house effect $\dot{E}_{gr} = P_{out}$ and we know that $P = \dot{E}_{tidal}$. Therefore, the green house effect is given by

$$\dot{E}_{gr} = \frac{\alpha}{2-\alpha} \dot{E}_{tidal}.$$

Now, the temperature with the single layer atmosphere model is

$$T_{gr} = \sqrt[4]{\frac{\dot{E}_{tidal} + \dot{E}_{gr}}{4\pi \cdot R^2 \cdot \sigma}}.$$

Our simulation yields $T_{gr} = 328.162K$. Because both of these temperature falls within the interval for liquid water (between $273\ K$ and $373\ K$), we can say that liquid water is present on our Blanet. Since the Blanet is hypothetical, we decided to cover 95% of the Blanet's surface by water. This will induce significant tidal effects which we will elaborate on in the following section.

2.4 Habitat

Our alien habituates underwater near hydrothermal vents. These thermal vents provide our alien with a relatively constant temperature, but above all, our alien is dependent on the consumption of small organisms that live around these vents. We think the strong tidal differences will create a turbulent environment and because of that is forced to migrate from time to time to other hydrothermal vents, thus forcing it to adapt to changing environments.
The hydrogen sulfide that is emitted by the hydrothermal vents will be the main energy source for the thioautotrophic organism. Our alien will hunt these organisms and get its energy from these organic compounds.

2.4.1 Tidal Buldge and water level

Now, let the center of the Blanet be our origin. For a given point $\vec{r}$ on the Blanet at given time t, the moon's contribution to the water level at $\vec{r}$ (in the same direction as $\vec{r}$) at given time t is

$$H_{moon}(\theta_1(t)) = \frac{M_{moon} r^4}{2 M_{Blanet} D_Q^3} (2\cos^2(\theta_1(t)) - \sin^2(\theta_1(t)))$$

and the black hole's contribution is

$$H_{BH}(\theta_2(t)) = \frac{M_{BH} r^4}{2 M_{Blanet} D_P^3} (2\cos^2(\theta_2(t)) - \sin^2(\theta_2(t))).$$

The total contribution to the water level is

$$H_{tot}(t) = H_{moon}(\theta_1(t)) + H_{BH}(\theta_2(t)).$$

The two angles θ_1 and θ_2 (see appendix II) are time-dependent due to the spin of our Blanet, which we set to 1 rotation per day (same as the Earth). Again, for simplicity, we set the spin of the Blanet perpendicular to the plane of its orbits. For the description and full derivation of these results, see Appendix II. Let r be the distance between the surface and the center of the Blanet. For a point on the surface of the Blanet, the water level on that point (with respect to the center of the Blanet) is given by

$$Z(t) = H_{tot}(t) + r.$$

If we plot $Z(t)$ for every point on the surface of the Blanet, we will get the tidal bulge at time t. This is the blue ellipse in figure 1. When there is no tidal force, H_{tot} will be zero for any point on the surface and the water level $Z(t)$ will simply be constant at r (with respect to the center of the Blanet). The water level in the absence of tidal forces gives us the blue circle in figure 1. Both the blue ellipse and the circle are magnified for visualization.
The yellow line in 1 represents the location of our alien. This line will of course rotate along with the spin of the Blanet. We can now investigate the development water level at the yellow line with respect to the surface (at distance r to the center of the Blanet). To do this, we simply plot $H_moon(t)$, $H_{BH}(t)$ and $H_{tot}(t)$ with respect to time. Note that the initial position of the moon is the same as in section 2.2.3.

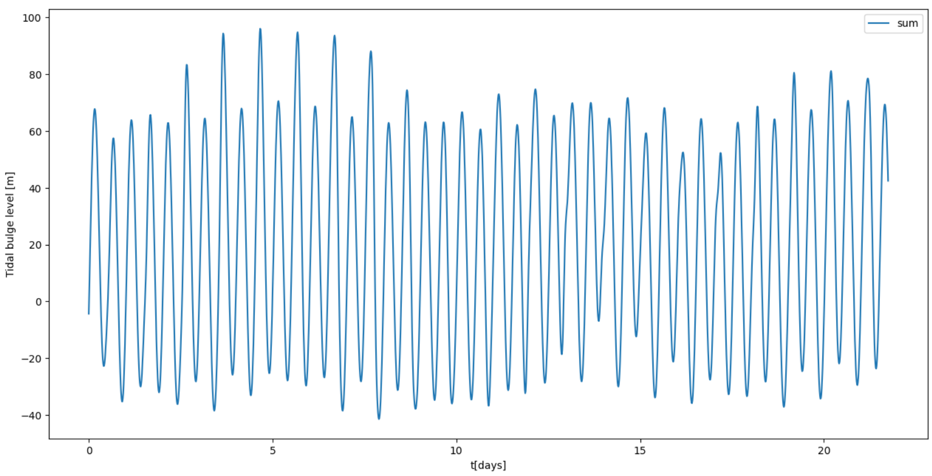

Figure 4: The nett contribution of water level $H_{tot}(t)$ due to the tidal forces exerted by both the black hole and the moon

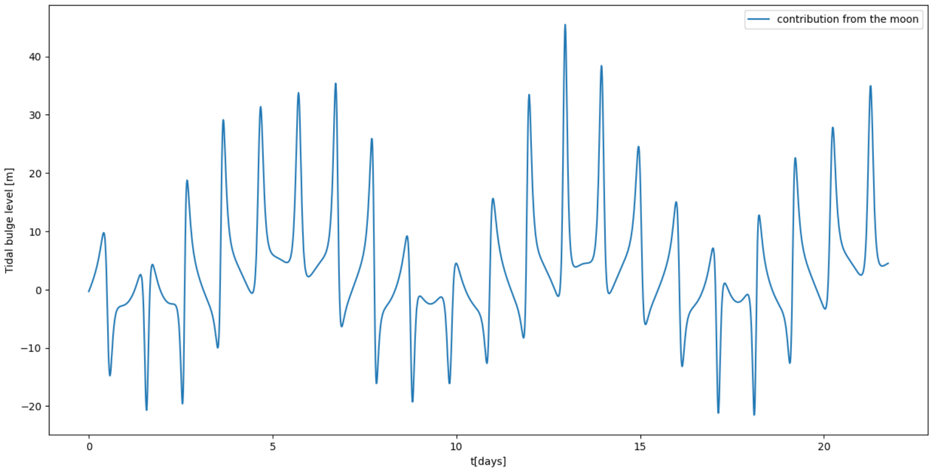

Figure 5: The water level $H_{moon}(t)$ contributed by the moon

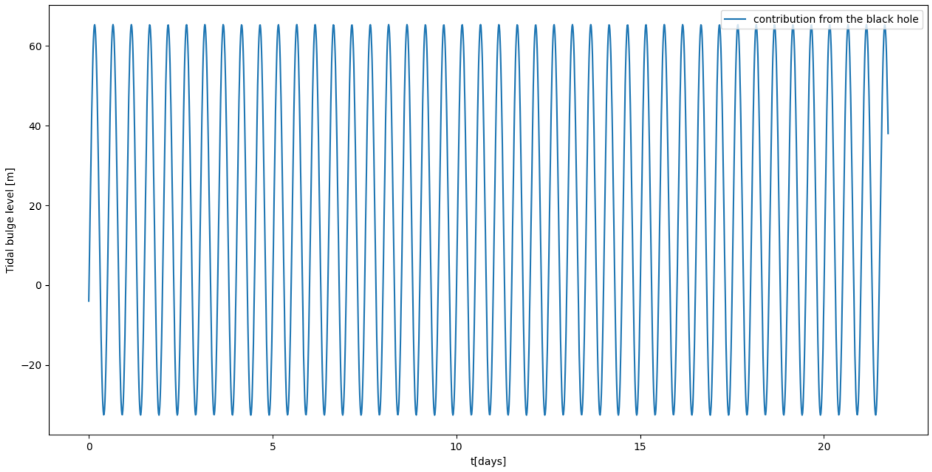

Figure 6: The water level $H_{BH}(t)$ contributed by the black hole

In figure 4 we can see that the change in water level is relatively irregular. This is because the contribution of the moon to the water level is irregular due to the precession in its orbits. The irregularities in the contribution of the moon are clearly shown in figure 5. The black hole, on the other hand, gives a stable and periodic contribution to the water level due to its circular orbit (see figure 6). We can compare the contributions of the black hole and the moon and the nett change in water level in figure 7. We can see that when the peaks of H_{moon} and H_{BH} are aligned, the nett change in water level is the most significant. And when the peaks of H_{moon} and H_{BH} are anti-aligned (when the maxima of H_{moon} meet the minima of H_{BH} and vice versa), the nett change in water level is minimized. In figures 4 and 7, we can also observe the fact that there are (approximately) two maxima and two minima per day. The maxima represents flood and the minima represents drain. The tidal difference (height difference between maxima and minima) can be observed in 4 and 7 between 80 to 120 meters. Compared to Earth, the largest tidal difference measured is 16.3 meters [34]. Due to the significant tidal difference that varies on a daily basis, the environment on the surface could be harsh and inhabitable. Therefore, our alien is most likely to live at the bottom of the ocean. However, the enormous tidal interactions

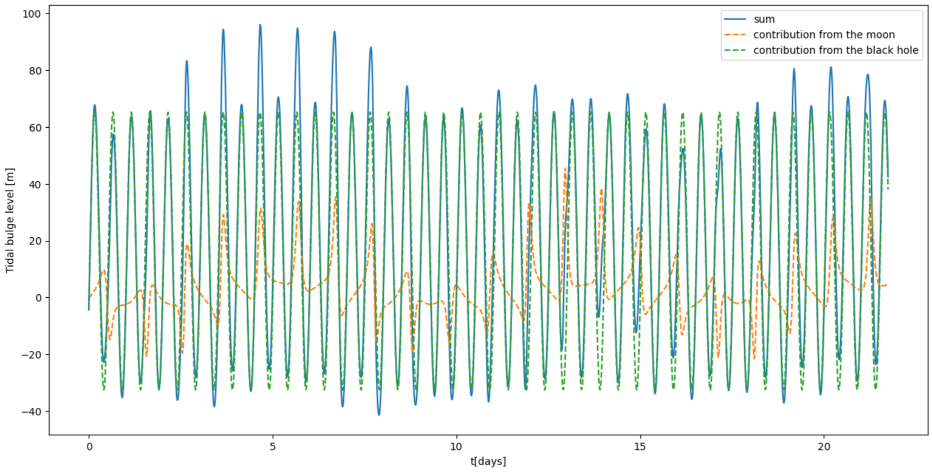

Figure 7: The nett water level and the contributions of the black hole and the moon

could cause strong and unpredictable tidal currents, which still poses a threat against our alien.

2.4.2 Tidal current

The tidal range on the Blanet is between 80 and 120 meters. This has major consequences for the tidal current of the ocean. The tidal current is the current of the water caused by tidal range. Tidal currents are influenced by a number of factors, like the tidal range, the shape and size of the ocean basin, the depth of the water and the location of the tide-generating forces. Because there are many factors that play a role in the calculation of the tidal current, it is virtually impossible to calculate this with our current knowledge. We will therefore estimate the mean tidal current based on the largest tidal current ever recorded on earth. Saltstraumen is a small canal in Norway where the tidal currents can reach up to 40 km/h [31]. The Saltstraumen canal is a very small and shallow canal with a tidal range of 9 meters. Because there is a less strong tidal current in a deep, wide ocean, and the tidal range is about 10 times as large, we think that the the tidal current of the Blanet is 40 km/h as well. This estimation is pure hypothetical and is not supported with scientific evidence.
Because the tidal current depends on a number of factors, the tidal currents are different over time. We think there are periods of low tidal currents and high tidal currents. Because so many factors play a role we think the periods of high tidal currents occur at random. This provides life on this Blanet with a turbulent environment.

2.4.3 Formation of the Equatorial Ridge

Since we have placed the black hole, the Blanet and the moon all on the same plane, we can expect that the tidal interactions are the strongest on this plane. And since we have set the spin of the Blanet perpendicular to this plane, we can expect the tidal interaction on the Blanet to be the strongest around the equator. Because of this, we hypothesize that this area will receive the most amount of tidal force, thus receiving a high amount of tidal heating. The tidal heating in turn will heat the rock in the mantle of the Blanet, creating magma. Because of the pressure difference between the magma and the mantle, the buoyancy force will push the magma to its buoyancy level. When the magma reaches close to the surface, water seeping through fissures will heat up to around 400°C. As the water is heating up, the pressure will increase causing the water to shoot up through underwater chimneys called hydrothermal vents, where the temperature of the water is 350°C. Around the equator, a lot of these hydrothermal vents are formed. This area, with a high concentration of hydrothermal vents is called the *Equatorial Ridge*. This ridge is rich in chemicals and chemical reactions. This is due to the fact that while the water shoots up, many chemicals dissolve and are transported to the ocean, where it will rain down to the ocean floor. These chemicals include Mn^{2+}, H_4SiO_4, $FeOOH$, MnO_2, CH_4, Fe^{2+}, $HexSy$, H_2 and H_2S.

2.4.4 Size of the Equatorial Ridge

The *Equatorial Ridge* will span around the entire equator. Assume the Equatorial Ridge to be symmetrical around the equator (see figure 8). We can now evaluate the surface area of the Equa-

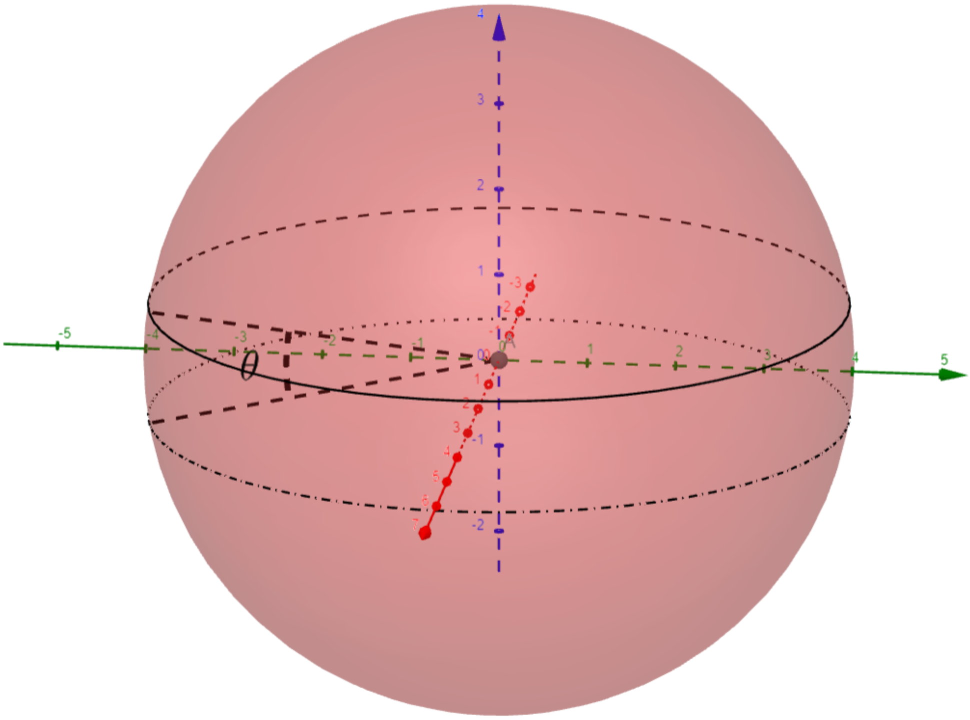

Figure 8: Schematic drawing of the Equatorial Ridge

torial Ridge (between the two black circles in figure 8). Say the Blanet's radius is R. First, we parameterize the partial circle arc of angle $\frac{\theta}{2}$ as

$$r(\phi) = R\cos(\phi)\hat{i} + R\sin(\phi)\hat{j}.$$

The arc length element is

$$ds = \left|\frac{dr}{d\phi}\right| d\phi = R \cdot d\phi.$$

We can now make a solid of revolution around the z-axis ($\hat{k}$-direction), and obtain the surface

$$\begin{aligned} A &= 2 \cdot 2\pi \int r \cdot ds \\ &= 4\pi \int_0^{\frac{\theta}{2}} \sqrt{R^2 - R^2\sin^2(\phi)} \cdot R \cdot d\phi \\ &= 4\pi R^2 \int_0^{\frac{\theta}{2}} |\cos(\phi)| d\phi. \end{aligned}$$

Assume $0 \leq \frac{\theta}{2} \leq \frac{\pi}{2}$, we now have

$$A = 4\pi R^2 \cdot \sin\left(\frac{\theta}{2}\right).$$

This is the area of the Equatorial Ridge. We assume that on our Blanet $\theta = \frac{\pi}{24}$. Plugging in the values of our Blanet, we found out that the area of the Equatorial Ridge is 33359812.572 km^2, which is almost twice the size of Russia. We hypothesize that there will be one hydrothermal vent per 20 km^2, making this ridge the home of about $1.7 \cdot 10^6$ hydrothermal vents.

2.5 Elemental and chemical composition

The composition of our Blanet is fairly simple. Since we have hypothesized our Blanet to be Earth-similar, we can say that the Blanet has the same elemental composition as the Earth and the structure of the Blanet also consists of three main parts: the crust, the mantle and the core. The most abundant elements in the Blanet's crust are displayed in the following table Just like

Elements	Approximate % by weight
O	46.6
Si	27.7
Al	8.1
Fe	5.0
Ca	3.6
Na	2.8
K	2.6
Mg	1.5

Table 2: Elemental composition of the Blanet's crust (the same as the Earth, the data comes from [15])

Earth, the mantle of the Blanet consists of moderate amount of Si and high concentration of Fe and Mg. The core of the Blanet consists mostly of Fe and Ni [15].
In previous sections, we hypothesized the presence of a large amount of volcanic activity. On Earth, 99% of the gas molecules released by volcanic activities are H_2O, CO_2 and SO_2. [35] A significant amount of these gases will therefore be found in the atmosphere of our Blanet. For SO_2, we propose a value of 10 ppm, which is 10 times more than on Earth [32]. Because we hypothesized the Blanet to be Earth similar, the most part of the atmosphere should still consists of nitrogen. [27] However, the presence of molecular O_2 is quite unlikely due to the absence of O_2 producing organisms. Water vapor on Earth takes roughly 0-3 % of the Earth's atmosphere. [27] Based on the assumption that 95% of the Blanet's surface is covered by water (and a large amount of volcanic activities), we can say that roughly 4.5% of the Blanet's atmosphere consists of water. Our estimation of the composition of the Blanet's atmosphere can be found in the following table:

Molecule	Estimated %
N_2	75
CO_2	20
H_2O	4.5
other	0.5

Table 3: Estimated atmosphere composition of the Blanet.

In appendix III, we have estimated the pH of acidic rain to be 3.1. This is caused by the abundance of CO_2 and SO_2 released by volcanic activities. For this calculation, we did not take any base molecules into account that can absorb the H^+-ions. We can assume that there are plenty of base molecules in the ocean on the Blanet. Therefore, the pH value of acidic rain can be used as an underbound for the acidity of the ocean. Meanwhile, the ocean of the Blanet will be more acidic than the Earth's ocean due to the abundance of volcanic activities. According to [??], early Earth ocean around 4.0 Ga had a pH of 6.6. Since the early Earth also has lots of volcanic activities, we can compare our Blanet to early Earth. Therefore, we can estimate that the pH of our ocean is between 3.1 and 6.6.

Figure 9: An artist impression of the scenery of the Blanet. The ocean and the volcanoes are depicted.

2.6 Scenery

In our system there is no star present, only a black hole and a moon, so there is no light on our Blanet. The moon and the black hole exert tidal forces on the Blanet, as a result there is volcanism and there are mountains. Furthermore, 95% of the total surface is covered with (acidic) water. The Tidal forces cause huge waves and there is a region in the ocean with a large density of hydrothermal vents, called the Equatorial Ridge. Each of the vents create small ecosystems. In figure 9 an artist impression of the Blanet is depicted.

3 Origins of life

3.1 Hydrothermal vents

The high concentration of hydrothermal vents in the Equatorial Ridge makes it a suitable location for the emergence of life on the Blanet. Many have suggested that life on Earth began near hydrothermal vents[5, 11, 26] , for there must be a high concentration of (bio)material for life to arise. Hydrothermal edifices are porous which means that the vents can capture these materials [26]. This would also explain why the concentrations would not decrease due to them being washed away by the strong tidal currents. Another advantage hydrothermal vents have is that it creates pH, temperature and ionic concentration gradients providing energy sources[5]. Of course, there has to be a lot of luck involved in this process.

3.2 Amino acids

Hydrothermal vents can create amino acids from a high concentration of small inorganic compounds[11]. This means that some of the amino acids created by the hydrothermal vents on the Blanet would be similar to the amino acids found on earth. Another way to get amino acids is through a meteoric input [3]. It is likely that the Blanet is constantly hit by small meteorites bringing some other amino acids. However, we think that this meteoric input is lower than the input the Earth experienced during the Late Heavy Bombardment. Because of this we thing that the amino acids produced by geochemical reactions and the meteoric input combined provide life on the Blanet with 17 amino acids, instead of the 20 we know from life on Earth. The main reason for this decision is that we think that it would be highly unlikely that the exact same amino acids seen on Earth would be the same as on the Blanet. The amino acids we use for life on the Blanet are the same as on Earth, without proline, tyrosine and tryptophan. It is hard to say what the exact consequences are for life to exclude three amino acids as we have never encountered an organism that uses a different amount of or different amino acids. We hypothesize that this will lead to a reduction in complexity, as less different proteins can be created. We assume that the difference in amino acids will not lead to any problems with folding or resistance of the proteins.

3.3 Other building blocks

We assume that life on the Blanet also uses RNA and DNA to provide memory and maintenance. As the environments on the Blanet are similar to those on the prebiotic earth, we think it is possible that the same molecules were created. Evidence was provided for the possibility of the creation of RNA in prebiotic environments recreated in a lab[4]. We also assume that ATP and phospholipids are present on the Blanet to provide for energy and containment for life.

4 Emergence of the Wobble

The emergence of single cells out of organic compounds happened near the heat of hydrothermal vents (figure 10A and B). When cells need to copy DNA during every division, mutations will arise stochastically. The amount of mutants that arise in a population of cells depends on the mutation rate. We assume that the mutation rate of these small cells will be high a similar to anaerobic deep-sea archaeon on Earth, with an average mutation rate of 85.01 x 10-10 per cell division per nucleotide site [9].
After the emergence of single thioautotrophic cells near the heat of hydrothermal vents, the population of these cells started to grow (figure 10C), but the limited area around the vents provided a limited amount of resources. Individual cells in a growing population will be in competition with each other when nutrients are limiting. When the ecological presents itself, intraspecies competition can lead to natural selection for the diversification of a population [10].

4.1 From unicellular to multicellular

Random mutations lead to a lot of different sorts of cells and the competition against each other resulted in a natural pressure of the cells to eliminate other cells. During this time a mutation occurred that allowed some cells to obtain energy from organic compounds. With this mutation, they lost the autotrophic ability to obtain energy from sulfide from the hydrothermal vents and a new line of organisms emerged: hunting cells that obtained their energy from consuming other, smaller cells (figure 10D). These hunting cells were larger, moved slower and divided slower than the still autotrophic cells. The cells required some adaptations to obtain a sort of hunting strategy. Through random mutations and selection, a specific line of hunting cells arose which were able to secrete small ‘cell-like’ vesicles with parts of DNA in it, that were able to perform specific functions, kept together with a mucus layer (figure 10E). In this situation, the organism started to look like a transition of a unicellular to a multicellular organism (figure 10F). Living in a co-operation of multiple cells brought benefits that the single cells did not have; they were able to move better and forage better [8].
Another reason for the growth of multicellular life was that the hunting cells were able to hunt other hunting cells, becoming its own predator. Cells that are exposed to a predator, are far more likely to acquire adaptations toward multicellularity, forming colonies with a high probability of survival and a high reproduction rate. Colonies of cells increase the probability of survival because predators will not be able to eat the cells as easily as when the cells live individual [22].

4.2 The Wobble

The hunting cells started to look more like clumps of cells, with one larger "mother cell" in the middle, containing all the DNA. But being a larger organism came with its downsides as well. It was much more affected by the strong tidal currents, so it had to adapt to surviving outside of the habitual zone of the hydrothermal vents for long periods of time. Stronger DNA repair systems in the mother cell helped to protect the DNA, but for maintaining a source of energy under adverse conditions, the organism has developed a different strategy over time. Instead of consuming the thioautotrophic organisms, the Wobble started to live in symbiosis with these cells, providing them with a supply of sulfur, which in turn provides the Wobble with a small amount of the produced energetic organic compounds. (figure 10G). This symbiosis is based on the idea of the symbiosis between the Riftia pachyptila (also known as the giant tube worm) and an intracellular sulfur-oxidizing bacterium on Earth [23].

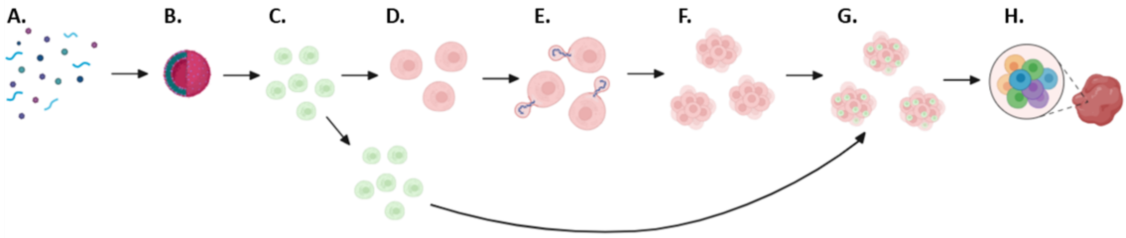

Figure 10: The different steps of the evolution of the Wobble.

At this point, the Wobble is fully emerged (figure 10H). Because the Wobble consists of mostly small differentiated cells which contain only small parts of DNA, the Wobble is able to quickly generate new cells because it does not have to copy all its DNA, but only the genes that are needed to perform the necessary function (see figure 11).

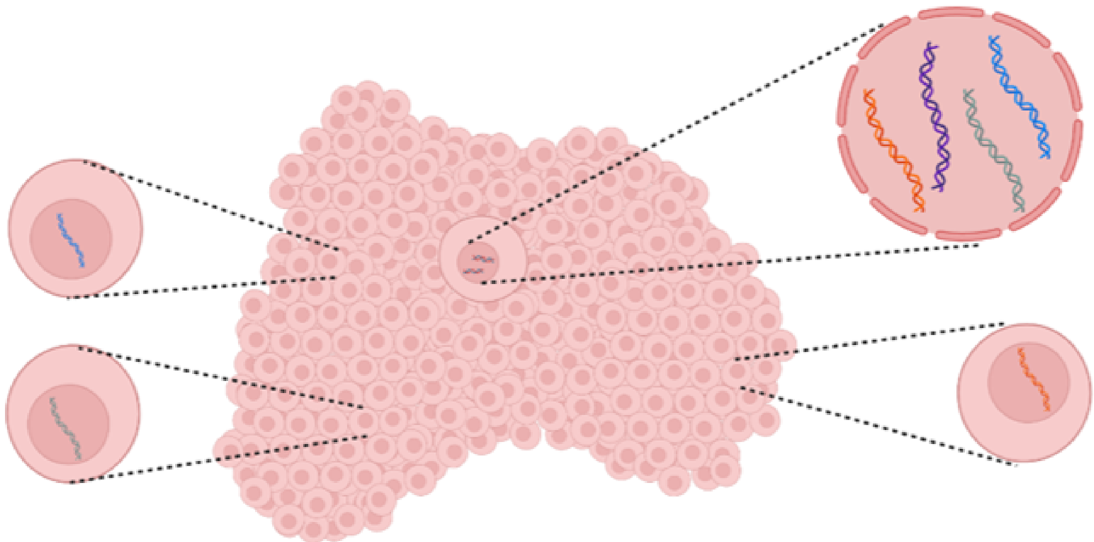

Figure 11: The Wobble and its differentiated cells with specific parts of DNA and one mother cell containing all of the DNA.

To answer the question how the Wobble solves the problem of CCEMMM we have taken inspiration from life on Earth.

The cells of the Wobble are made out of a phospholipid bilayer membrane to provide for containment. For the catalysation of reactions, the Wobble produces proteins made out of 17 different

amino acids. The Wobble is able to produce most of the amino acids themselves, but not all. These amino acids have to come form the consumption of other organisms that are able to produce these amino acids.
In order to sustain life it needs energy. The Wobble has two strategies to get energy. The first one is to consume other organisms and breaking down their organic molecules, producing ATP. The other way the Wobble gets energy is from a symbiotic relationship with thioautotrophic bacteria. Because there is virtually no oxygen gas (O_2) on the Blanet for aerobe reactions, the thioautotrophs are adapted to reduce elemental sulfur (S) to hydrogen sulfide (H_2S). These bacteria use S as the electron acceptor, H_2 emitted by hydrothermal vents as electron donor and dissolved CO_2 as the carbon source. This produces ATP of which a small amount is given to the Wobble.
The movement of molecules within the organism is taken care of by water.
The Wobble uses DNA and RNA to provide it with memory. These molecules are made out of the same four nucleotides as that of life on Earth. tRNA coding for base triples is used to create proteins. However, the base pairs do not code for the same amino acids as on Earth. For example, a terrestrial organism would translate GGA to Glycine, while the Wobble would translate this to a different amino acid. Because of this, the Wobble translates the same DNA string different than terrestrial life.
Maintenance is regulated by fast cell replication and cell division.

4.3 Cell functions

4.3.1 Creator cell

Cell division will proceed differently in our Alien than on Earth. Given that the mother cell contains all of the DNA required for the creation of all the individual cells, a separate mechanism will be necessary to create new cells. The DNA needed for a new specialized cell is transported in a vesicle to the "creator" cells. The creator cells acquire the new DNA and cell division is initiated.
Essentially, cell division begins from the telophase because a nuclear envelope has to be formed, however the DNA is not copied. However, the organelles and other preparations for the division need to be completed before the division. Therefore, the creator cells produce the enzyme creatase which initiates the first stages of cell division: G0, G1, S and G2. It will wait for a specific signal to initiate the remaining stages. Most of the M phase will be skipped as the DNA present is not copied. The new DNA is transported in a vesicle which also contains an enzyme needed to initiate the production of the nuclear envelope (telophase) and another enzyme to induce cytokenesis.
The cell divides, with one daughter cell containing the DNA of the original creator and another daughter cell containing the DNA for a new specialized cell. The cell will first be in a juvenile state as the shape has not yet been determined by the new DNA. As the DNA is read, the membrane will take the shape according to the genetic code and be suitable for that specialized cell. It will complete this process as it migrates to the place in the organism where it will perform its function. Once it arrives, it will grow to a mature stage where it will be able to perform effectively.

4.3.2 Sensory cell

This hair-like structure on the outer layer of the Wobble serves as a means of sensing what is transpiring in the environment. The hairs function as antennae for signals and changes in the environment (see figure 12). Receptors on the surface of the hairs can detect a change in acidity and temperature. Furthermore, there are receptors that specialize in sensing the presence of prey. Additionally, they can detect a difference in water movement because the dragging force of the water on the cells is greater when the flow rate of the water is higher.[16] Between the hair like structures on the outer layer of the organism lies a mucus layer which function is to protect the cells from breaking apart by the strong currents or the high temperature and acidity level near the hydrothermal vents. It keeps the Wobble together and also protects the cells from external factors. In order to survive the harsh conditions near the hydrothermal vents the membrane contains ether linked lipids to ensure stability.

4.3.3 Hunter cell

These elongated cells are specialised to contract and expand (see figure 12). Multiple of these cells together can form arm-like structures. These Arm-like structures capture a prey or predator which were detected with the sensory cells on the outside of our alien. The type of movement in cells is called amoeboid movement [36] which involves the extension and retraction of pseudopodia, comparable to the movement with muscles. The hair like structures will send a signal to the hunter cells to extend in the direction of the signal, it will engulf the prey and pull it into the organism to break it down with the use of metabolic cells. They contain the same ether-bound lipids in their cell membranes as the sensory cells to ensure their stability when they come into contact with the harsh external conditions.

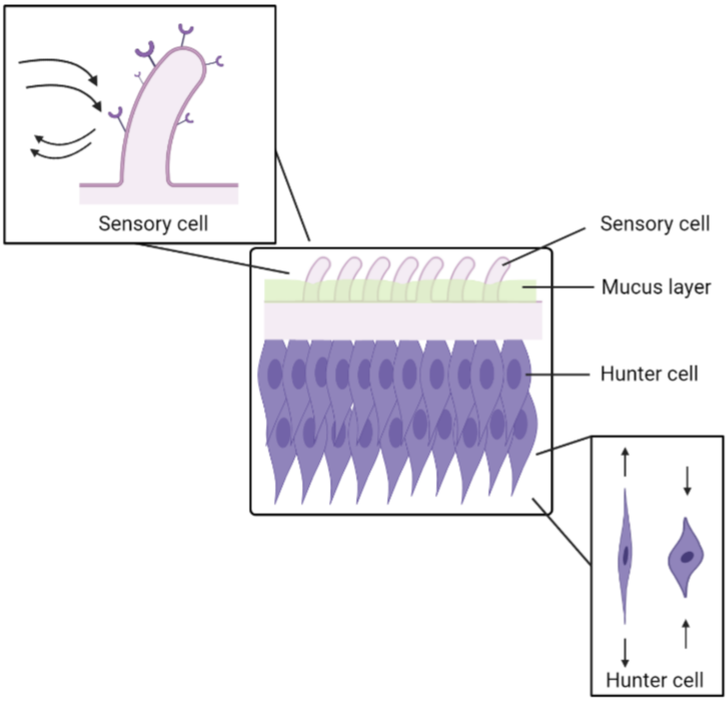

Figure 12: The Wobble outer layer containing sensory cells, hunter cells and mucus layer.

4.3.4 Metabolic cell

Once the Wobble has captured prey using the hunter cells, it is delivered to the metabolic cells. It contains a variety of enzymes that can break down a wide range of biomolecules, including lipids, carbohydrates, and proteins. The main enzymes present in the metabolic cells include glycosidases, proteases and sulfatases.
Glycosidases are enzymes that break down glycosidic bonds, which are bonds that link together carbohydrate molecules. Glycosidases can break down a variety of carbohydrate molecules, including sugars, starches, and glycogen. They work by hydrolyzing the glycosidic bonds between the carbohydrate molecules, releasing simple sugars that can be absorbed and used by the cell. [37] Proteases work by breaking down proteins into smaller peptides and amino acids. They work by hydrolyzing the peptide bonds between the amino acids that make up proteins, releasing individual amino acids that can be absorbed and used by the cell.[14] Sulfatases are enzymes that hydrolyze the sulfate esters, breaking the bond between the sulfate group and the organic molecule. This releases the organic molecule, which can then be absorbed and used by the cell.

[18]The catabolic processes to break down complex molecules into simple components contributory to the release of energy that can be used by the Wobble.

4.3.5 Symbiosis cell

These cells will absorb thioautotrophic organisms which it will have a symbiotic relationship with to exchange materials and energy. This will be crucial to survive long dormant periods where the alien will not be near any hydrothermal vents. The hunter cells are activated by the sensory cells, but if a specific signal of the thioautotrophic prey is recognized, the prey will be transported into a symbiosis cell. This will be a relatively rare cell as its function only becomes important after the cell survives being swept away from a hydrothermal vent by the strong currents. It would be relatively large and energy consuming to create so it would not be energetically favourable to create many or have many of them at once.

4.4 Communication

On Earth, colonies of bacteria are able to communicate with each other using a process called quorum sensing. This process involves chemical signal molecules, called autoinducers. When the accumulation of autoinducers reaches a certain threshold or "quorum", it induces changes in the performance of the bacterial population. This may include the production of virulence agents, the production of biofilms or the onset of sporulation. Quorum sensing is an important mechanism that allows bacteria to adapt to their environment and coordinate their activities in order to survive and thrive. It allows bacteria to perceive the environment and to alter its behavior in response to changes of the cell-density in the colony. Higher, multicellular organisms on Earth use this type of molecules for synchronizing the activities of groups of cells. Quorum sensing-controlled processes are unproductive when carried out by individual bacteria, but they become valuable when these processes are performed by a larger number of cells. Quorum sensing blurs the line between prokaryotes and eukaryotes because it enables bacteria to act as a multicellular organism. Our alien uses a similar system for cell-to-cell communication. Through small signaling molecules the cells are able to work together as a multicellular organism. The extracellular concentration of these molecules can increase or decrease depending on the cell density of the colony. The cells in the core of the colony are also able to communicate with each other by septal junctions; a gated intercellular communication that are similar to the gap junctions found in eukaryotic cells on Earth.

5 Cell division

Now we will consider the type of cell proliferation that is advantageous for our specific life form. Our alien is a multi-cellular colony in which each cell has its own function. There will be a relatively large mother cell which is able to excrete DNA for any specialised cell that is needed for the organism. Only the mother cells contain all the DNA. Once the mother excretes DNA, it only transcribes the DNA necessary for the processes that this cell has to carry out. Because not all the DNA has to be copied, DNA transcription is more efficient and allows the quick creation of new cells, depending on which cell is most favourable at that moment. Because of this rapid way of cell division, the organism is highly resistant to changing conditions and cell death.

6 Dormancy

Due to the strong tidal currents and the high migration rate of the Wobble, it is possible for the wobble to become trapped in an unfavorable environment without any nearby hydrothermal vents for an extended period of time, the basic requirements for growth are not available. In these circumstances, the Wobble needs a defense mechanism to survive. On Earth, all microorganisms are exposed to periods of stress that inhibit growth occasionally. Many bacteria and fungi endure these periodic stresses by entering a hardy, non-reproducing state, which is often called a quiescence or dormancy. The Wobble uses the same concept of a dormancy, in which it

is metabolically active, non-replicating and energy-saving so the organism can be resistant to many environmental challenges. Just like some bacteria on Earth, the Wobble can survive in such a state for long periods of time [1].
When the wobble gets stuck in unfavorable conditions, its most important task is to protect the mother cell containing all its DNA. Apoptosis will begin to take place in the outer layer of cells and these cells are broken down. The dead material of the cells is used to harden the outer mucus layer of the wobble into a strong shell that protects the remaining cells and the mother cell from the environment (see figure 13).

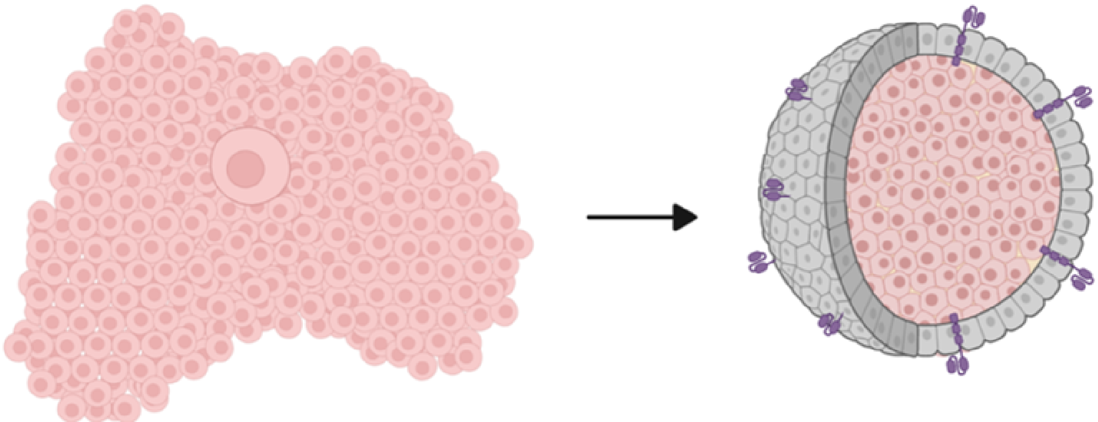

Figure 13: The Wobble when it goes into dormancy during unfavorable circumstances.

A major physiological outcome of these changes is a decreased permeability of the outer membrane of the Wobble and the inner cells will be protected against toxic elements, changing temperatures, changing pH and food scarcity.
The remaining cells contain a lot of storages of necessary elements to keep the Wobble alive. A property of the dormancy is the use of the accumulated sulfur, stored in the cells of the Wobble. This sulfur will be reduced to hydrogen sulfide by the thioautotrophic cells in the Wobble and once the sulfur is depleted it will switch to a slow breakdown and digestion of the thioautotrophic cells.
Woven through the hard shell of the wobble during dormancy are special receptor proteins from the sensory cells, which can detect acidity, temperature and the presence of important elements. Once these receptors detect favorable changes in the environment, the Wobble releases its shell and has starts to consume a lot to grow the cells and the supplies he has left during the dormancy. In this fast-growing state, the Wobble releases a specific hormone which is important for reproduction.

7 Genetic background

7.1 Composition

Considering the harsh conditions on our Blanet, DNA as we know it would not be sustainable. The extremely high acidity levels and high temperatures near the hydrothermal vents could cause irreparable damage on the genetic information carried by the organism. Since most of the cells are protected by the mucus layer, the threat is not so imminent, but to ensure the survival of the species, it has adapted its genetic information to survive in those conditions. This is necessary as this increases its chances of survival, since it might drift too close to hydrothermal springs, where the mucus layer does not provide sufficient protection.
High acidity levels can affect the structure and function of DNA. The phosphate groups that make up the backbone of the DNA molecule are sensitive to changes in pH and can become ionized or dissociated at high acidity levels. This can cause the DNA molecule to become more reactive and prone to chemical modification or degradation.

High temperatures can cause DNA molecules to denature and the hydrogen bonds between the complementary base pairs can break. This can lead to changes in the DNA sequence and ultimately, genetic mutations. [13]

To ensure the survival of life, the genetic information needs to be protected with a additional mechanisms. These can include the following.
Use of DNA repair mechanisms. Many organisms have mechanisms in place to detect and repair damaged DNA. These mechanisms can help to maintain the integrity of the DNA molecule and prevent mutations from occurring. Reverse gyrase is an enzyme that can alter the structure of DNA and is observable in prokaryotes on Earth. Some organisms can adapt to high temperatures and other conditions due largely to reverse gyrase. It reduces the rate of double-stranded DNA breakage. Reverse gyrase is thought to add positive supercoils to the DNA molecule, increasing the stability of the molecule, which may help protect DNA from damage caused by high temperatures. In addition to being able to detect damaged DNA, reverse gyrase may also recruit a protein coat to the site of damage by cooperative binding.
It facilitates proper annealing and inhibits the improper aggregation of denatured DNA sections and recognizes damaged DNA and functions as a molecular splint to stop DNA cleavage close to the lesion, keeping damaged DNA in a salvageable conformation. [12]
Because there are only 17 amino acids but still 64 different base pairs, the chances of a mutation leading to the coding of a different amino acid is reduced. There are more triplet codes that code for a specific amino acid, meaning that the chance is lower for the altered base pair to code for a different amino acid.

7.2 Circular DNA

Circular DNA is a type of DNA molecule that is arranged in a circular shape rather than a linear one. Circular DNA genomes are found in many bacteria, including Escherichia coli, as well as in several viruses. Having a circular DNA genome has various benefits. [17]
Circular DNA molecules don't have ends, hence there is no need for a particular mechanism to duplicate the ends of the molecule. This results in efficient replication. As a result, genome replication is more effective and less prone to errors.
It also provides genetic stability. Compared to linear DNA genomes, circular DNA genomes are less likely to degrade or lose genetic information. This may be crucial for preserving the organism's genomic integrity throughout time.
Circular DNA genomes occasionally feature certain areas that are more or less accessible to the enzymes responsible for regulating gene expression. As a result, gene expression can be precisely regulated in response to various circumstances.
For creatures with compact genomes or restricted cell space, a circular DNA genome can be crammed more tightly into the cell than a linear DNA genome. [20]

7.3 Genome

As we now know, the genetic material is maintained in circular DNA and is shielded from the environment by specific mechanisms. Furthermore, chromosomes will be used to store the DNA, with one chromosome designated for each type of cell including one chromosome assigned to the fundamental tasks that every cell must perform. In total, this amounts to six chromosomes.
Genome size is usually measured by various techniques such as fluorescence in situ hybridisation. However, we must provide a rough estimate of the genome size of the Wobble. The mother cell will have the full genome size because it carries all of the genetic material. Since the mother cell can carry out many different processes, its genome is likely to be relatively large. Therefore, we hypothesise that the genome size of the mother cell and the specialised cells is approximately 20 Mb for the specialist cells and 120 Mb for the mother cell. [2]

8 Reproduction

The wobble itself makes use of asexual reproduction to create new generations of its species. This type of reproduction does not involve the fusion of gametes or the exchange of genetic material. The Wobble can produce offspring that are genetically identical to itself. This is because the offspring are produced from a single parent and do not inherit genetic material from a second parent. This is favourable in the environment as it may be close to impossible to find a competent mate of the same species but opposite sex to exchange DNA if you can be swept away by the strong currents at any moment. Asexual reproduction means it is not reliant on the frequency and availability of the species and it is possible at any moment.

8.0.1 Horizontal gene transfer following dormancy

For the succession of the species, horizontal gene transfer is a common phenomenon. This mechanism is most remarkable in the process after dormancy. Once the Wobble awakes, it will produce the necessary enzymes to re-establish all processes that were active preceding the dormant stage. Furthermore, the enzymes initiate the excretion of a vesicle of DNA containing the genetic code concerning the dormant stage. Other Wobbles capture the vesicle with the genetic code for successful dormancy, which is subsequently integrated into the genetic code of the mother cell such that all offspring will contain the successful DNA. This process is beneficial to the species because positive mutations are spread to ensure the progress of the species. This is also a common phenomenon for hyperthermophiles on earth to ensure their own species survival [25].

9 Detection

9.1 Detection of the Blanet and Wobble

Detection of an object in the universe is often done by measuring the light it emits or by detecting its radiation. These methods are difficult to work with when considering a planet orbiting a non-active black hole, however it is possible. This is because there is no light due to the black hole and no detectable radiation. But there is detectable thermal radiation coming from the Blanet. Every object that has temperature, and therefore emits thermal radiation, radiates in the infrared. The infrared is a region in the electromagnetic radiation spectrum where wavelengths range from 700 nanometers (nm) to 1 millimeter (mm). This is detectable if the apparent magnitude of the Blanet is smaller than 34, which is the lowest apparent magnitude the James Webb Telescope can detect.[29] This can be checked by using the formula for the apparent magnitude:

$$m = -2.5 \log \frac{f}{f_0} \tag{1}$$

In the formula for the apparent magnitude 1 f is the flux of the object with the unknown apparent magnitude and f_0 is the standard apparent magnitude of the star Wega.
The flux of the Blanet can be calculated by dividing the luminosity of the Blanet divided by the surface of the sphere with the radius the distance from the Blanet to planet Earth. The luminosity is calculated with:

$$L = \sigma 4\pi R^2 T^4 \tag{2}$$

In the formula for the luminosity is the σ the Stefan-Boltzmann constant, the R is the radius of the Blanet and T is the temperature of the Blanet (295K - 328K).
The flux of the Blanet is than calculated with:

$$f = \frac{L}{4\pi D^2} \tag{3}$$

D is the distance between the Blanet and the Earth. Our Blanet is a hypothetical planet, therefore this distance is not defined but in this model we will set it to the same distance of Earth to the closest star, Alpha Centauri (4.367 light years).

If the values of our Blanet and of the standard star Wega are filled in the formulas 3, 2 an1 we get that the apparent magnitude of our Blanet ranges between approximately 22.857 and 23.318 (we get this interval due to the temperature that ranges from 295K-328K). These values for the apparent magnitude are lower than 34 and therefore it is possible to detect the infrared radiation emitted by the Blanet. To check that this radiation is infrared radiation Wien's displacement law can be used.

$$\lambda_{max} = \frac{b}{T} \tag{4}$$

This equation 4 gives the wavelength (λ_{max}) at which the power per unit wavelength is maximum. The rest of the variables are the temperature (in Kelvin) on the surface of the Blanet, T and Wien's constant $b \approx 2,89777 \times 10^{-3}$Km.
When the values for our Blanet are filled in we get:

$$\lambda_{max} = \frac{2,89777 \times 10^{-3}}{295} \approx 9.823 \times 10^{-6} m \tag{5}$$

$$\lambda_{max} = \frac{2,89777 \times 10^{-3}}{328} \approx 8.835 \times 10^{-6} m \tag{6}$$

These values are in the interval of the infrared radiation.
The Blanet its infrared radiation can be measured provided that the Blanet is facing the Earth and therefore is in front of the black hole, because when it is behind the black hole the radiation is not able to reach the Earth.
The James Space Telescope is accurate enough to observe wavelengths in the infrared and therefore it is able to detect such a Blanet.[29]

Existing detection of life methods rely on DNA, this depends on reverse transcriptase and DNA polymerase. In life on Earth this depends on the five bases A, G, U, C and T. In life on Earth enzymes are highly specific, DNAs with different bases will not be picked up. So in order to detect life, it is needed to find the DNA or the alternative to DNA that the alien is using.

Life detection methods could also rely on amino acids. Proteins on the Blanet are made out of 17 different amino acids and are homochiral. This homochirality could be detected.
Living organisms always require a Gibbs Energy source, in the case of the Wobble this is obtained with symbiosis with sulfur-reducing bacteria. These bacteria are capable of reducing elemental sulfur (S) into hydrogen sulfide (H2S). By reducing sulfur stored by the Wobble, the Wobble is able to produce ATP.
The building blocks of the Wobble are the elements carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur. The elements C, H, O, N, P and S therefore need to be available on the Blanet. The Blanet has an atmosphere, these elements may be present in the atmosphere and therefore can be detected. This would give an indication of the scenery and life on the Blanet. To detect the Wobble itself, signatures of its life, for example amino acids, need to be found. This is difficult due to its habitat, near a hydrothermal vent causing a strong currents and due to the location of the Blanet, near a black hole.

Another method to detect life is to use the heat that comes from a planet in the form of thermal radiation (infrared radiation). The theoretical amount of radiation of the Blanet could be calculated this could be compared to the measured amount. If this differs from the theoretical value one could introduce the idea of a life form inhibiting the Blanet that causes this difference.
To summarize, the detection of the Wobble is difficult but possible, by detecting elements in the atmosphere of the Blanet, finding amino acids, its DNA or by the thermal radiation emitted by the Wobble.

9.2 Ladder of life detection

In table 4 the ladder of life detection of the Blanet is depicted.

Detection of life ladder			
Category	Feature	Ambiguity	Detectability
Habitability	Liquid water	High	Easy (some hard)
	Energy source: hydrothermal vents		
	Raw materials: SiO_2 Fe, Mg, Ca, K, Na [6]		
	CHNOPS/atmospheric composition		
Suspicious biomaterials	General indicators (patterns, metal distribution, homochirality)	Medium	Some easy, some hard
	Monomers: amino acids, nucleic acids, lipids	Medium	Some easy, some hard
	DNA/RNA	Low	Hard
Life	Metabolism and Evolution	Low-medium	Hard
	Growth and cellular reproduction and Evolution	Low	Hard
	Evolution	Low	Not possible

Table 4: The ladder of life detection of the Blanet.

9.3 Predator-Prey simulation

In this section, we will discuss the detection of our alien based on the study of its population development. We will then make a simulation of the population of our alien in Pygame, based on the predator-prey model. The purpose of this simulation is purely to sketch an intuitive picture of the population development of our alien. It is obvious that we cannot model the population of our alien exactly with this model because there are simply too many unknown variables. However, we can still derive some interesting patterns from this simulation.

9.3.1 Simple predator-prey model

The predator-prey model is a simple and well-known mathematical model to simulate the population development between two groups. One group is called the predator and the other group is called the prey. As the name suggests, the predators hunt the prey. Mathematically this model is defined as the following set of differential equations:

$$\begin{cases} \frac{\mathrm{d}x}{\mathrm{d}t} = \alpha x - \beta xy \\ \frac{\mathrm{d}y}{\mathrm{d}t} = \delta xy - \gamma y \end{cases}$$

where x denote the population of the prey and y the population of the predator. The parameters α, β, γ and δ are real positive numbers governing the interaction between the two groups.
In our case, this model is not enough for three reasons:

1. The predator-prey model is too general for our case. It does not consider the effect that only a fraction of the prey population can come in contact with the predators because the preys are locally confined in the hydrothermal vent, while the predators can only stay at the edge of the hydrothermal vent. The predators are only allowed to hunt the preys at the edge of the hydrothermal vent.

2. The resources in the hydrothermal vent are finite, meaning that the population of the preys cannot grow infinitely.

3. The predator-prey model does not consider environmental perturbations. In our case, we hypothesized that there will be significant tidal currents flowing across the equatorial ridge. This perturbation is not incorporated in the predator-prey model.

Therefore, we choose to customize the predator-prey model to study the population development of our alien and its prey.

9.3.2 Game customization

(a) (b)

Figure 14: Screenshot of our predator-prey model simulation: (a) a screenshot of the general setup, (b) a screenshot of the randomly generated tidal current.

We will extend and customize the simple predator-prey model in the form of a game. This game is written in Pygame (source code see [7]). A screenshot of the game can be found in 14. The rules are as follows:

1. There are two spiecies: the alien and the prey. At the beginning of the game, each starts with a certain number. We denote the amount of aliens as N_{alien} and the amount of preys as N_{prey}. Once the game has started, both species will be in random walk. The preys are born and confined in the hydrothermal vent (see the red circle in figure 14), while the aliens are born at the edge of the hydrothermal vent. The aliens are attracted to the preys but can only stay near the edge of the hydrothermal vent. (The temperature inside the hydrothermal vent is way too high for the aliens.) Because we assumed that the hydrothermal vents are uniformly distributed on the equatorial ridge, we can use periodic boundaries to restrict the aliens. This means that once an alien exits the frame, it reappears on the opposing side of the frame. We can describe this as

$$(x, y) = (x + \lambda_1, y + \lambda_2)$$

where x and y are the pixel coordinates in the frame and λ_1 and λ_2 the pixel length of the sides of the frame. The will simulate the incoming and exiting stream of aliens.

2. On every iteration of the game, there is a 0.09% chance that a random tidal current will be generated in the fol:

    - The duration T is randomly generated between 100 and 200 iterations, by uniform distribution. The tidal current will stop after T iterations.
    - The tidal current can be then described as a vector

    $$\vec{v}_{tidal}(r, \theta(t)) = (r \cdot \cos(\theta(t)), r \cdot \sin(\theta(t)))$$

    for $t \in [0, T]$, where r is uniformly chosen between 20 to 50 pixels. Note that the θ component of this tidal vector is time-dependent. Because of this, the tidal current is able to change direction within its duration. The $\theta(t)$ is defined as

    $$\theta(t) = \theta_0 + \omega \cdot t$$

where θ_0 is uniformly chosen between 0 and 2π and ω between $-\pi$ and π. The tidal vector is the displacement vector that only applies to the aliens. This means that the aliens will be carried away by the tidal vector while the preys remain in the hydrothermal vent. An example of this vector can be found in figure 14.

3. The birth of the alien and prey is also randomized. We do this by introducing a randomly chosen countdown for the birth of the two species. The birth countdown for aliens is denoted as T_{alien} and for preys as T_{prey}. Initially these two are both randomly chosen integers between 0 and 50. After T_{alien} number of iterations, new aliens will be born at the edge of the hydrothermal vent. The amount of new aliens is

$$X_{alien} = \lfloor \alpha \cdot N_{alien} \cdot N_{prey} \rfloor$$

where α is the birth rate of the aliens, and N_{alien} and N_{prey} are the amount of aliens and preys before the new aliens are born. $\lfloor\rfloor$ denotes the floor function which converts a real number to an integer. After new aliens are born, the countdown for birth of new aliens will be randomly rechosen as an integer between 0 and 50. Similarly, after T_{prey} iterations, new preys will be born inside the hydrothermal vent. The birth of new preys can be defined as

$$X_{prey} = \left\lfloor \beta \cdot N_{alien} \cdot N_{prey} \cdot \left(1 - \frac{N_{prey}}{M_{prey}}\right) \right\rfloor$$

where β is the birth rate of preys, and N_{alien} and N_{prey} the amount of aliens and preys before the new preys are born. Note that we have introduced a new term $\left(1 - \frac{N_{prey}}{M_{prey}}\right)$, where M_{prey} denotes the maximal amount of preys allowed in a hydrothermal vent. This will stop the population of preys from growing once it has reached the maximal capacity. After the new preys are born, the countdown for birth of new preys will be randomly rechosen as an integer between 0 and 50. The amount of aliens and preys are now

$$N_{alien} \mapsto N_{alien} + X_{alien}$$

and

$$N_{prey} \mapsto N_{prey} + X_{prey}.$$

4. The health points of the aliens are denoted as HP. On every iteration, the aliens risk of dying by starvation. This means that on every iteration their HP will be decreased by

$$HP \mapsto HP - \gamma \cdot HP$$

where γ is the hunger factor between 0 and 1. Once the HP of an alien has reached below 1, on every iteration, there is 1% chance that this alien will die.

5. The aliens can hunt the preys within their radius of capture. This radius is 15 pixels from the position of each alien. On every iteration, every prey within the radius of capture of an alien will have 10% chance to be killed by that alien. For each prey an alien has killed, the alien receives 10 extra HP.

9.3.3 Simulation result

We can simulate the above customized predator-prey model in Pygame. The code of this simulation can be found in our [7]. In our simulation, we choose a frame of 500 pixels by 500 pixels with the hydrothermal in the middle with a radius of 50 pixels. We start with 30 aliens and 100 preys. The aliens will initially have 100 HP each and the hunger factor γ is 0.1. The birthrate of the aliens α is 0.003 and the birthrate of the preys β is 0.8. For our simulation, we have 10287 iterations. The video of the simulation can be found in [7].
We can then plot the development of the population with respect to the iterations. In figure 15, we can see that the variations of population for both the aliens and the preys are quite chaotic. However, we can still derive some interesting patterns. We can see that when the population of aliens increases, the population of the preys will decrease. This is logical, since more aliens

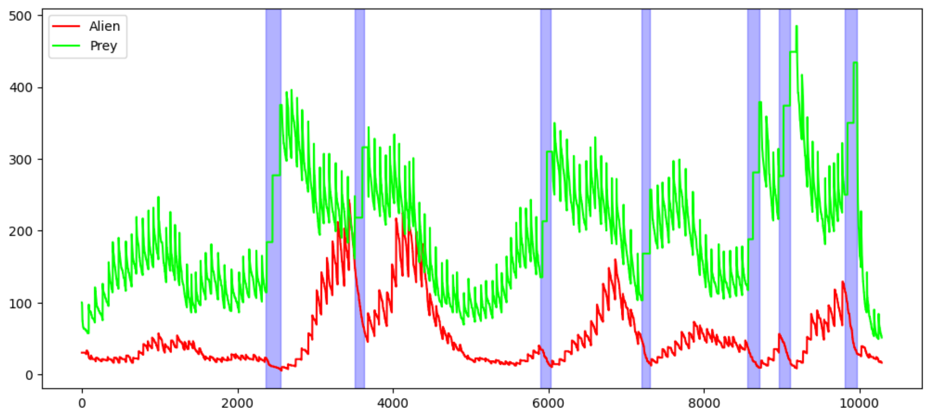

Figure 15: Predator-prey simulation of 10287 iterations: the green line denotes the amount of prey and the red line denotes the amount of aliens. The blue shaded area denotes the iterations when a randomly generated tidal current has taken its place.

means more preys will be killed. However, the population of the aliens will not keep growing. Because when the population of the preys decreases, there will be less food for the aliens. This means that more aliens will die of starvation and less aliens will be born. These patterns are the characterics of our predator-prey model. We can also observe the influence of the tide currents on the population of the two species. When there is tidal current (see blue shaded area in 15) we see that the population of the preys explodes while the population of the aliens decreases. This is logical, since the aliens cannot feed on the preys when being carried away by the current, while the preys themselves are not affected by the tidal currents and are able to reproduce freely until they reach the maximum capacity of the hydrothermal vent.

We can assign bio-signatures to the two species. We hypothesize that our preys feed on H_2S and our aliens are able to produce CO_2. If we can assume that there is a one-to-one relationship between the concentration of the H_2S-isotopes in the atmosphere and the population of the preys, and between the concentration of CO_2 and the population of the aliens, we can expect to find the similar patterns as in our predator-prey model, when we look at how the concentration of those two gases develops in time. However, this does not directly give us evidence of the existence of our alien and prey, since other type of organisms that are in similar predator-prey relationship, can deliver similar patterns as well. Therefore, these patterns can only serve as (suspicious) indicators for the existence of life and predator-prey relationship on our Blanet, but does not proof the actual existence of our particular alien and prey.

10 Final remarks

The Blanetary system is not a known system. At this moment, not a single Blanet has been detected. Previous studies [21] have discussed the possibilities of life on Blanets around super massive black holes. Those studies investigate the case when the Blanet is formed around the black hole. In our studies, we turn our focus to the case when the Blanet is captured by the (stellar mass) black hole. The reason we chose for this system is because we want to challenge ourselves to think of the possibilities of life in the absence of light and under enormous gravitational forces. However, because this system is entirely hypothetical, we have to make lots of assumptions and simplifications. For instance, we simplified our system to a circular restricted three-body problem. We have also neglected the friction of water with the surface of the Blanet and numerous other fluid dynamics. Last but not least, we choose our system to be Earth similar so we can use the same values and composition for our Blanet (such as the second Love number and the chemical composition).

Besides we made assumptions concerning the Equatorial Ridge. We could not found similar cases in literature. Therefore, we have estimated our own values for the size of the Equatorial Ridge and the density of the hydrothermal vents. For example, computation concerning the tidal currents was far beyond our knowledge and beyond the scope of this study. We estimated a current speed based on the highest recorded tidal current on Earth and we assumed that it occurs at random intervals as shown in the simulation of the population development of our alien. Furthermore, we have realized how complex life on Earth is. Since we are only familiar with life on Earth, it was difficult for us to come up with different solutions to problems compared to life on Earth. We have taken inspiration of cells compositions, bacteria and the mutation rate on Earth.

Finally, we want to shine light on the project itself. We are very grateful for the opportunity to learn from other disciplines than our own. We have gained much knowledge on topics we were not familiar with, such as the requirements of life and the working of planetary systems. During the lectures, the brainstorm sessions and while writing this report we have realised how complex life on Earth is and what a special place it is.

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A Appendix I: Three body calculation

A.1 Introduction

Our black hole-Blanet-moon system is a typical three-body system. Generally, there are no analytical solution to the three body problem. However, since we are working with a hypothetical system, we can reduce our system into a circular restricted three body problem. We assume that the two (relatively) massive bodies, the black hole and the Blanet, orbit around their common center of mass in circular orbits, while the third body (the moon) has no gravitational impact of the two massive bodies. In this section we will study the orbital dynamics of the moon using Lagrangian formalism. We will work with the generalized setting first and later on simulate the system using specific parameters.
Suppose we have two massive bodies M_1 and M_2. We set both of them on the x-axis and their center of mass at the origin. Suppose the two bodies are at distance R from each other. We denote the distance of M_1 to the origin as

$$r_1 = R \cdot \frac{M_2}{M_1 + M_2}$$

and the distance of M_2 to the origin as

$$r_2 = R \cdot \frac{M_1}{M_1 + M_2}.$$

The two massive bodies are rotating around the origin with constant angular velocity ω and there is a moon in this system with mass m at (x, y).

A.2 Orbital dynamics of the massive bodies

The two massive bodies are in circular orbits, which means that their orbital dynamics is fairly simple. By Kepler's third law, the angular velocity of M_2 orbiting around M_1 is

$$\omega^2 = G\frac{M_1 + M_2}{R^3}.$$

The orbital period of M_2 is

$$P = \frac{2\pi}{\omega}.$$

A.3 Rotating reference frame

Since the two massive bodies are rotating clock-wise at constant angular frequency ω, it is difficult to describe the motion of the moon in this system. However, we can set up our reference frame by rotating along with the two massive bodies. We can do this by applying a time dependent rotation matrix on our coordinates.

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix}.$$

We denote the coordinates in our rotating reference frame as (x, y) and in the initial (non-rotating) reference frame as (x', y'). Therefore, by applying the inverse of the clockwise rotation matrix we have

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}.$$

Note that

$$\dot{x'} = \dot{x}\cos(\omega t) - \omega \cdot x \sin(\omega t) - \dot{y}\sin(\omega t) - \omega \cdot y \cos(\omega t)$$

and

$$\dot{y'} = \dot{x}\sin(\omega t) + \omega \cdot x \cos(\omega t) + \dot{y}\cos(\omega t) - \omega \cdot y \sin(\omega t).$$

Therefore, we can write the velocity of the moon in the rotating reference frame as

$$\dot{x'}^2 + \dot{y'}^2 = \dot{x}^2 + \dot{y}^2 + 2x\omega\dot{y} - 2y\omega\dot{x} + \omega^2(x^2 + y^2).$$

Note that the kinetic energy of the moon in the rotating reference frame is

$$\begin{aligned} T &= \frac{1}{2}m(\dot{x'}^2 + \dot{y'}^2) \\ &= \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + 2x\omega\dot{y} - 2y\omega\dot{x} + \omega^2(x^2 + y^2)). \end{aligned}$$

The gravitational potential of the moon dependents on the distance between the moon and the two massive bodies. The total potential of the moon is

$$V = -\frac{GmM_1}{p_1} - \frac{GmM_2}{p_2}$$

where p_1 and p_2 are the distance between the moon and the massive bodies with

$$p_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2}$$

and

$$p_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2},$$

where (x_1, y_1) and (x_2, y_2) are the coordinates of the two massive bodies in our rotating reference frame. Note that these coordinates are stationary in our rotating reference (because we rotate along with them), but not in the original non-rotating reference frame. Now we can treat x_1, x_2, y_1, y_2 as constants. This is the reason why we choose the rotating reference frame in the first place.

A.4 Lagrangian and equations of motion

The Lagrangian of the moon is defined as

$$\begin{aligned} \mathcal{L} &= T - V \\ &= \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + 2x\omega\dot{y} - 2y\omega\dot{x} + \omega^2(x^2 + y^2)) + \frac{GmM_1}{p_1} + \frac{GmM_2}{p_2}. \end{aligned}$$

Using the Lagrange equation

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathcal{L}}{\partial \dot{q_j}}\right) - \frac{\partial \mathcal{L}}{\partial q_j} = 0$$

where q_j represents independent variables in $\mathcal{L}$, we obtain

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathcal{L}}{\partial \dot{x}}\right) - \frac{\partial \mathcal{L}}{\partial x} = 0$$

and

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathcal{L}}{\partial \dot{y}}\right) - \frac{\partial \mathcal{L}}{\partial y} = 0.$$

Note that

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial \mathcal{L}}{\partial \dot{x}}\right) &= \frac{\mathrm{d}}{\mathrm{dt}}\frac{1}{2}m(2\dot{x} - 2y\omega) \\ &= \frac{\mathrm{d}}{\mathrm{dt}}(m\dot{x} - y\omega) \\ &= m\ddot{x} - m\omega\dot{y}, \end{aligned}$$

and

$$\frac{\partial \mathcal{L}}{\partial x} = \frac{1}{2}m(2\omega\dot{y} + 2\omega^2 x) - \frac{GmM_1(x-x_1)}{p_1^3} - \frac{GmM_2(x-x_2)}{p_2^3}$$
$$= m\omega\dot{y} + \omega^2 x - \frac{GmM_1(x-x_1)}{p_1^3} - \frac{GmM_2(x-x_2)}{p_2^3}.$$

This gives us the first equation of motion

$$\ddot{x} = 2\omega\dot{y} + \omega^2 x - \frac{GM_1(x-x_1)}{p_1^3} - \frac{GM_2(x-x_2)}{p_2^3}$$

Similarly, we can obtain the second equation of motion by evaluating the y-component of the Lagrange equation:

$$\ddot{y} = -2\omega\dot{x} + \omega^2 y - \frac{GM_1(y-y_1)}{p_1^3} - \frac{GM_2(y-y_2)}{p_2^3}.$$

These are the equations of motion of the moon in our rotating reference frame.

B Appendix II: Tidal bulge and water level estimation

B.1 Introduction

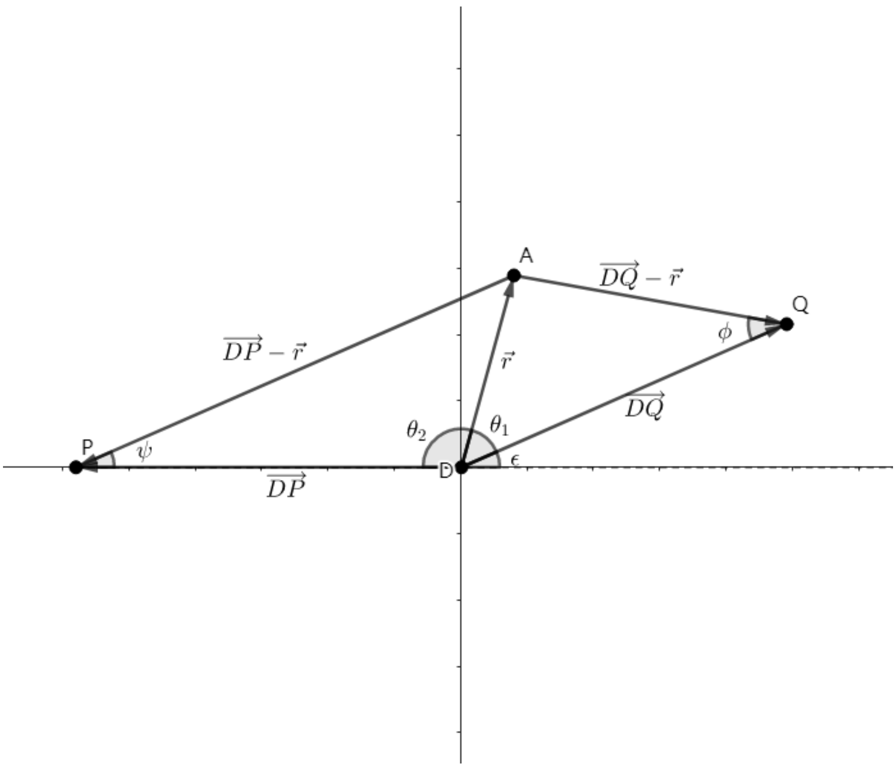

Figure 16: Schematic sketch of the setup

This section is aimed to get a better understanding at the mathematical principles behind the tidal bulge. We will only use rough approximation here, which means we will not take fluid dynamics into account but rather estimate the size and orientation of the tidal bulge based on simple classical mechanics. For the calculation, we assume water as an idealized liquid that always has enough time to form a bulge and has no friction with the surface of the Blanet.

Let the Blanet be at the origin $O = D$, the moon at point Q and the black hole at point P. De angle $\epsilon \in [0, 2\pi]$ is defined as the angle of the rotation of the moon with respect to $\overrightarrow{DP}$. Since our reference frame rotates around the black hole at the same angular velocity as the Blanet, $\overrightarrow{DP}$ is stationary. Let A be a arbitrary point on the Blanet, with $\overrightarrow{OA} = \vec{r}$. The test mass m is situated at $\vec{r}$.

B.2 Acceleration towards the moon

We first set our x-as parallel to $\overrightarrow{OQ}$. We define $\theta_1 \in [0, 2\pi]$ starting from $\overrightarrow{OQ}$. The angle ϕ is defined as the angle between $\overrightarrow{DQ} - \vec{r}$ and $\overrightarrow{DQ}$. The acceleration of the test mass m due to the moon is

$$GM_{moon}\frac{\overrightarrow{DQ} - \vec{r}}{|\overrightarrow{DQ} - \vec{r}|^3}.$$

But note that the Blanet is also getting accelerated towards the moon at

$$GM_{moon}\frac{1}{|\overrightarrow{DQ}|^2}\hat{x}$$

where $\hat{x}$ denotes the x-axis direction (parallel to $\overrightarrow{DQ}$). If we set our reference frame on the Blanet, the total acceleration of the test mass is then

$$\vec{a}_{moon} = GM_{moon}\frac{\overrightarrow{DQ} - \vec{r}}{|\overrightarrow{DQ} - \vec{r}|^3} - GM_{moon}\frac{1}{|\overrightarrow{DQ}|^2}\hat{x}.$$

We can write $\overrightarrow{DQ} - \vec{r}$ as

$$\overrightarrow{DQ} - \vec{r} = |\overrightarrow{DQ} - \vec{r}|(\cos(\phi)\hat{x} - \sin(\phi)\hat{y}).$$

Note that in our case, the radius of the Blanet is way smaller than the distance between the Blanet and the moon. Therefore, ϕ is small. We can then use the following approximation:

$$\cos(\phi) \approx 1$$

and

$$\sin(\phi) \approx \tan(\phi) \approx \frac{r\sin(\theta_1)}{D_Q}$$

where r and D_Q denote the length of $\vec{r}$ and $\overrightarrow{DQ}$ respectively. We can also write $|\overrightarrow{DQ} - \vec{r}|^2$ as

$$|\overrightarrow{DQ} - \vec{r}|^2 = DQ^2 - 2rD_Q\cos(\theta_1) + r^2.$$

Since r^2 is small compared to D_Q^2, we can say that

$$|\overrightarrow{DQ} - \vec{r}|^2 \approx D_Q^2 - 2rD_Q\cos(\theta_1) = D_Q^2\left(1 - \frac{2r}{D_Q}\cos(\theta_1)\right).$$

Recall the Taylor expansion

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + \cdots \approx 1 + x.$$

Substitute for $x = \frac{2r}{D_Q}\cos(\theta_1)$ and only take the first order approximation, we obtain

$$\frac{1}{|\overrightarrow{DQ} - \vec{r}|^2} \approx \frac{1}{D_Q^2}(1 + \frac{2r}{D_Q}\cos(\theta_1)).$$

Thus, the acceleration of the test mass can be approximated by

$$\begin{aligned}
\vec{a}_{moon} &= GM_{moon}\frac{\overrightarrow{DQ}-\vec{r}}{|\overrightarrow{DQ}-\vec{r}|^3} - GM_{moon}\frac{1}{|\overrightarrow{DQ}|^2}\hat{x} \\
&\approx GM_{moon}\frac{1}{|\overrightarrow{DQ}-\vec{r}|^2}\left(\hat{x}-\frac{r\sin(\theta_1)}{D_Q}\hat{y}\right) - GM_{moon}\frac{1}{|\overrightarrow{DQ}|^2}\hat{x} \\
&\approx GM_{moon}\frac{1}{D_Q^2}(1+\frac{2r}{D_Q}\cos(\theta_1))\left(\hat{x}-\frac{r\sin(\theta_1)}{D_Q}\hat{y}\right) - GM_{moon}\frac{1}{D_Q^2}\hat{x} \\
&\approx \frac{GM_{moon}r}{D_Q^3}(2\cos(\theta_1)\hat{x}-\sin(\theta_1)\hat{y}) - \frac{2GM_{moon}r^2\sin(\theta_1)\cos(\theta_1)}{D_Q^4}\hat{y}
\end{aligned}$$

Since $\frac{r^2}{D_Q^4} \approx 0$, we have

$$\vec{a}_{moon} = \frac{GM_{moon}r}{D_Q^3}(2\cos(\theta_1)\hat{x}-\sin(\theta_1)\hat{y}).$$

B.3 Acceleration towards the black hole

Similarly, we can calculate the acceleration towards the black hole. Now we set our x-axis parallel to $\overrightarrow{DP}$. The total acceleration of a test mass at $\vec{r}$ towards the black hole is

$$\vec{a}_{BH} = GM_{BH}\frac{\overrightarrow{DP}-\vec{r}}{|\overrightarrow{DP}-\vec{r}|^3} - GM_{BH}\frac{1}{|\overrightarrow{DP}|^2}\hat{x}.$$

By similar approximation, we arrive at

$$\vec{a}_{BH} = \frac{GM_{BH}r}{D_P^3}(2\cos(\theta_2)\hat{x}-\sin(\theta_2)\hat{y}).$$

Note that here $\hat{x}$ is parallel to $\overrightarrow{DP}$ and we define $\theta_2 \in [0,2\pi]$ as the angle between $\overrightarrow{DP}$ and $\vec{r}$ counted from $\overrightarrow{DP}$. In general, we have

$$\theta_2 = \pi - (\theta_1 + \epsilon).$$

B.4 Potential energy and height of tidal bulge

Now that we have calculated the acceleration, we can work out the potential of their corresponding force field along $\vec{r}$. The force on the test mass towards the moon is defined as

$$\vec{F}_{moon} = m\frac{r}{D_Q^3}(2\cos(\theta_1)\hat{x}-\sin(\theta_1)\hat{y}).$$

The force on the test mass towards the black hole is defined as

$$\vec{F}_{BH} = \frac{r}{D_P^3}(2\cos(\theta_2)\hat{x}-\sin(\theta_2)\hat{y}).$$

The potential delivered by $\vec{F}_{moon}$ along $\vec{r}$ is

$$\begin{aligned}
V_{moon}(r) &= -\int_0^r \vec{F}_{moon}\cdot d\vec{r} \\
&= -GM_{moon}\int_0^r m\frac{r}{D_Q^3}(2\cos(\theta_1)\hat{x}-\sin(\theta_1)\hat{y})\cdot(\cos(\theta_1)\hat{x}-\sin(\theta_1)\hat{y})dr \\
&= -GM_{moon}\int_0^r m\frac{r}{D_Q^3}(2\cos^2(\theta_1)-\sin^2(\theta_1))dr \\
&= -\frac{GM_{moon}m}{2}\frac{r^2}{D_Q^3}(2\cos^2(\theta_1)-\sin^2(\theta_1)).
\end{aligned}$$

Similarly, the potential delivered by $\vec{F}_{BH}$ along $\vec{r}$ is

$$V_{BH}(r) = -\frac{GM_{BH}m}{2}\frac{r^2}{D_P^3}(2\cos^2(\theta_2) - \sin^2(\theta_2)).$$

By conservation of energy, we can say these potential energy V_{moon} and V_{BH} can be converted into a displacement h of the test mass in its corresponding force field in the $\vec{r}$ direction from $\vec{r}$. Therefore:

$$V = -\int_0^h \vec{F}_g \cdot \vec{ds} = -\int_0^h G\frac{mM_{Blanet}}{(r+s)^2} + G\frac{mM_{moon}}{(D_Q - r - s)^2}ds.$$

Since $D_Q >> r$, the gravity delivered by the moon is negligible comparing to the gravity delivered by the Blanet. Also, because h is small, we can assume that the gravity delivered by the Blanet is relatively constant. This gives us the following relationship

$$V = -G\frac{mM_{Blanet}}{r^2} \cdot h.$$

Solving for h yields the following result: the displacement due to the moon is

$$H_{moon}(\theta_1) = \frac{M_{moon}r^4}{2M_{Blanet}D_Q^3}(2\cos^2(\theta_1) - \sin^2(\theta_1))$$

and the displacement due to the black hole is

$$H_{BH}(\theta_2) = \frac{M_{BH}r^4}{2M_{Blanet}D_P^3}(2\cos^2(\theta_2) - \sin^2(\theta_2)).$$

At a certain position $\vec{r}$, H_{moon} and H_{BH} are the contributions to the height of the tidal bulge along $\vec{r}$. The total height of the tidal bulge at $\vec{r}$ (in the $\vec{r}$ direction) will be

$$H_{tot} = H_{moon}(\theta_1) + H_{BH}(\theta_2).$$

B.5 Spin and water level

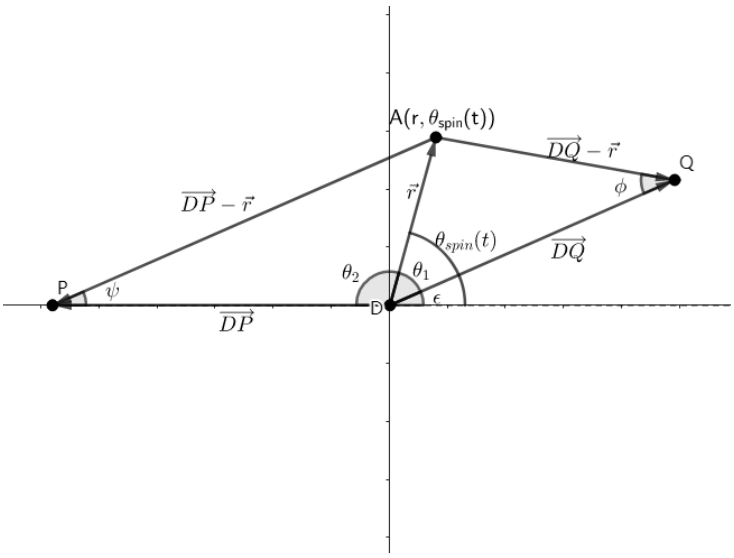

Figure 17: Schematic drawing of the setup

Now we can let the Blanet have a certain spin and choose one location on the surface of the Blanet, say A, to measure the water level (see figure 17). In polar coordinates we have $A = (r, \theta_{spin}(t))$. Here, r is the distance between the initial water level and the center of the Blanet.

We define the angle $\theta_{spin}(t)$ as the angle between $\vec{A}$ and the x-axis. Let the Blanet have a clockwise spin with angular velocity ω_{Blanet}. We can write $\theta_{spin}(t)$ as

$$\theta_{spin}(t) = \theta_{spin,0} + \omega_{Blanet} \cdot t,$$

where $\theta_{spin,0}$ is the initial angle between $\vec{A}$ and the x-axis. Now, θ_1 of $\vec{A}$ is defined as

$$\theta_1(t) = \theta_{spin}(t) - \epsilon(t)$$

and θ_2 of $\vec{A}$ is defined as

$$\theta_2(t) = \pi - \theta_{spin}(t).$$

The increase/decrease of the water level at $A(r, \theta_{spin}(t))$ due to the tidal bulge is

$$H_{tot}(t) = H_{moon}(\theta_1(t)) + H_{BH}(\theta_2(t)).$$

C Appendix III: Acidic rain

Now we can try to estimate the acidity of the (acidic) rain. The two main acidic gases that we take into consideration here, are CO_2 and SO_2 [35]. Both of them can react with water with the following reaction:

$$CO_2 + H_2O \xrightleftharpoons{K_{a,1}} H^+ + HCO_3^-$$

and

$$SO_2 + H_2O \xrightleftharpoons{K_{a,2}} H^+ + HSO_3^-.$$

The corresponding equilibrium reactions are

$$K_{a,1} = \frac{[H^+] \cdot [HCO_3^-]}{[CO_2]}$$

and

$$K_{a,2} = \frac{[H^+] \cdot [HSO_3^-]}{[SO_2]}$$

where we denote the equilibrium constants of the these two reactions as $K_{a,1}$ and $K_{a,2}$ respectively. From [24], we found that $K_{a,1} = 4.3 \cdot 10^{-7}$ and $K_{a,2} = 1.54 \cdot 10^{-2}$. For now, we ignore the fact that HCO_3^- and HSO_3^- can also release H^+ ions, because their contributions are negligible. By Henry's law, we can calculate the concentration of CO_2 and SO_2 in water. Let p_1 and p_2 be the partial pressure of CO_2 and SO_2 respectively. The concentrations of CO_2 and SO_2 in water are

$$X_1 = [CO_2] = k_1 \cdot p_1$$

and

$$X_2 = [SO_2] = k_2 \cdot p_2$$

where k_1 and k_2 are the Henry's constants for CO_2 and SO_2. From [19], we found that $k_1 = 0.034\ mol/(L \cdot bar)$ and $k_2 = 1.3\ mol/(L \cdot bar)$ at $298.15\ K$. By table 3, we found the values of partial pressures to be

$$p_1 = 0.20 \cdot 3 \cdot 1,01325 = 0.0206703\ bar$$

and

$$p_2 = 1 \cdot 10^{-5} \cdot 3 \cdot 1,01325 = 3.03975 \cdot 10^{-5}\ bar.$$

Therefore, we have

$$X_1 = 0.0206703\ mol/L$$

and

$$X_2 = 3951675 \cdot 10^{-5}\ mol/L.$$

Because $K_{a,2} >> K_{a,1}$, the SO_2 reaction is more dominant in this case. We can now make the following reaction table for SO_2 which yields:

	SO_2	H^+	H_2
Begin	X_2	0	0
Reaction	$-x$	$+x$	$+x$
End	$X_2 - x$	x	x

Table 5: Reaction table for $SO_2 + H_2O \xrightleftharpoons{K_{a,2}} H^+ + HSO_3^-$

$$\frac{x^2}{X_2 - x} = K_{a,2}.$$

Assume $x << X_2$, we now have

$$x \approx \sqrt{K_{a,2} \cdot X_2} = 7.80101243429 \cdot 10^{-4}\ mol/L.$$

This is the amount of H^+ produced in the SO_2 reaction. Similarly we can now make a reaction table for the CO_2 reaction. However, now the share the common H^+ ion: which yields

	CO_2	H^+	H_2
Begin	X_1	x	0
Reaction	$-y$	y	$+y$
End	$X_1 - y$	$x + y$	y

Table 6: Reaction table for $CO_2 + H_2O \xrightleftharpoons{K_{a,1}} H^+ + HCO_3^-$

$$\frac{(x+y)y}{X_1 - y} = K_{a,1}.$$

Again, assuming $y << X_1$, we now have

$$y^2 + xy - K_{a,1} \cdot X_1,$$

which has solution

$$y = \frac{-x + \sqrt{x^2 + 4 \cdot K_{a,1} \cdot X_1}}{2} \approx 1.12319676161 \cdot 10^{-5}\ mol/L.$$

This is the amount of H^+ produced by the CO_2 reaction. The total concentration of $[H^+]$ is of course

$$[H^+] = x + y \approx 7.91333211045 \cdot 10^{-4}\ mol/L,$$

which gives us a pH of 3.1.