# An analysis of marine light patterns

A thesis presented for the degree of
Bachelor in Physics

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**Abstract**

This paper aims to explain the appearance of several marine light phenomena observed in the Indian Ocean. The distinction is made between giant rotating light wheels with curved spokes and light balls shooting up from the depths of the ocean. Connecting these two phenomena are their strong geographical limitations, the fact that observations have only started since the 1900's and that they have drastically decreased over the past few decades. A description of these two phenomena is given based on reports collected by several authors who have also studied the phenomena. The different ways in which lights could appear in the ocean are explored. The ones involving marine organisms are fluorescence, phosphorescence and bioluminescence, of which bioluminescence seems to be the most promising mechanism, mainly due to its ability to be triggered by outside sources and to emit very bright, sudden lights. For these same reasons dinoflagellates seem to be the most promising organism emitting the lights and these have therefore been further discussed. It seems they are mainly triggered by fast changes in the ambient flow of water and very fast pressure changes. Since the Indian Ocean is known to be seismically active, earthquake lights are also discussed, but since a lot of their characteristics remain unknown it is hard to draw any conclusions about them. Next, the possible theories behind the emergence of the patterns are studied. K. Kalle earlier proposed a theory that seismic waves could be the cause of the appearance of both light wheels and light balls. The light balls would be seismic P-waves made visible by bioluminescence and the light wheels would be caused by the interference pattern of two different circular seismic sources, reflecting both to the ocean surface and the ocean bottom several times. The first part could be true, but the second part is shown to be lacking in detail. A theory involving light wheels turning with their center points on the horizon states that the observed wheels are actually parallel light beams that only seem like wheels because of optical illusion. These beams could be the result of the lensing of surface waves of light being uniformly emitted from below. Finally a new theory is proposed which involves the magnetic fields that ships are known to have, induced by the Earth's magnetic field, and the resulting flow of salt ions in water, which could possibly trigger bioluminescence. However, the analysis in this paper doesn't provide a satisfactory solution to the proposed problem.

# Contents

# 1 Acknowledgements

First and foremost I would like to thank my supervisor Leo Maas. His touch is visible in nearly every aspect of this thesis, but especially in my analysis of the magnetic field problem. Much of the information on bioluminescence in dinoflagellates that is presented in this thesis came to light in a relatively short talk with Francesca Sangiorgi, for which I am very grateful. I would also like to show gratitude to the NIOZ institute, because the experiments that are part of this thesis were made possible by the material and staff made available by them. Of this staff I would explicitly like to thank Sven Ober, who provided me with an experimental approach to every aspect I wanted to study and Anna Noordeloos en Kirsten Scholten-Kooijman, without whom my experiment would have come to a quick end, because they helped me to cultivate a population of dinoflagellates. Additionally, I would like to thank Taco de Bruin for the use of the extremely sensitive camera he personally provided, which helped me in realizing that no modern camera on its own is able to provide a clear image of the biolumiscence I am interested in.

## 2 Introduction

Over the last hundred years observations have been made of a variety of bioluminescent, fluorescent and phosphorescent phenomena at sea. The difference between these three is in the mechanism that causes them. Bioluminescence is triggered by a protein, luciferase, that can be oxidized and in this process light is emitted. Fluorescence is caused by the absorption of photons that excite electrons, after which the electrons immediately jump back, thereby emitting light. Phosphorescence works with the same mechanism but the electrons jump back slowly, thus the emission can still take place after no light has been absorbed for a while. Therefore, both phosphorescence and fluorescence are of abiotic origin. Bioluminescence can consist of different colors, but mostly white to blue light is emitted, and can be very bright. Fluorescent light has the same characteristics but is always bright and the emission cannot take place in the dark. Phosphorescence is mostly green and less bright, but can take place in the dark (Hanley III, 2011). Most of these phenomena are easily explained by the lighting up of certain organisms due to surface gravity waves caused by wind and ships that trigger the earlier mentioned processes. However, many cases have been reported on the appearance of patterns that cannot be explained by these simple waves. In these specific cases, roughly two different phenomena have been observed. The first of them is the appearance of giant light wheels with curved spokes, ranging from several meters to several hundred meters in diameter, spinning at high speeds around a center point with several spokes passing the ship per second. A sketch made by an observer on the Ms. Dione is displayed in figure 1 (Otto, 1979), where the different phenomena they observed are shown. Sketches made by combining observations from different reports are displayed in figure 2.

The other phenomenon that has been observed is that of balls, or patches of light, shooting up from the depths of the ocean. The balls start out small, but when they come close to the surface they expand and above the surface they explode into large discs of light above the water. These discs disappear in seconds afterwards. In all events the light that appeared was reported to be extremely bright, which would indicate strong bioluminescent triggering. Over the past hundred years that the observations have taken place, several theories have been developed aiming to explain the phenomena. None of them can however fully explain all the observations that have been made and because a possibly conclusive theory could involve aspects of several of the theories, I will briefly discuss all of them. A distinction is made in the theories between what they aim to explain, the source of the light or the emergence of the patterns, because this shows what theories are complementary and which are excluding with respect to each other. Though this distinction is not completely correct in all cases, it does offer a more structured view of the theories.

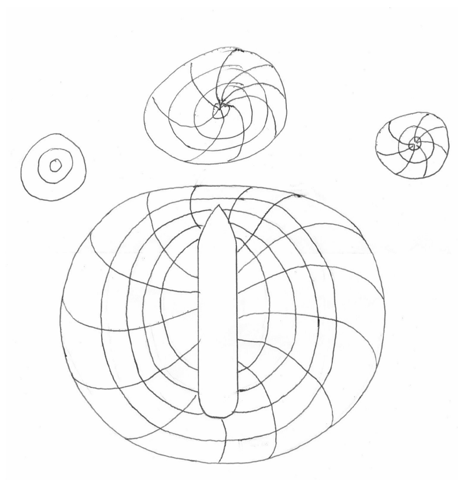

Figure 1: Sketch of light wheels as observed on board of the ship ms 'Dione'. (J.P. Molenaar 1978)

# 3 Observations

A short description of the observations of the light wheels and light balls is required in order to clarify what exactly we are trying to explain. Almost all of the reports on the luminous phenomena were originally published in the Marine Observer, but the reports used in this thesis were those collected by Kalle (Kalle, 1960), who collected seventy reports and by Corliss (Corliss, 1977), providing us with thirteen more, very extensive reports. All observations are mentioned here, even though some will later prove to be trivial. This is done because most observations are used as arguments in the theories, so putting them in perspective now will prove very useful later. Furthermore, with all these observations it should be noted that they have been made by sailors at night, who are suddenly surprised by bright lights that generally disappear after about twenty minutes, so that they do not have a lot of time to take in every aspect of the phenomenon. Therefore it could be that some of the observations are biased, so we will only look at any common denominators in the reports and leave any strange anomalies up to faulty observations. Firstly there will be further elaboration on different aspects of the phenomena, after which all common denominators of the different reports will be provided.

To start off, the aforementioned wheels have been reported to turn at high speeds around a center point and some reports indicate that they float up to a few meters above the sea surface, though the majority of the reports do not mention this peculiarity. A distinction can be made as in how this center point is positioned, since it has been reported to be indistinct somewhere on the horizon, next to the ship and not moving along with the ship and centred on the ship

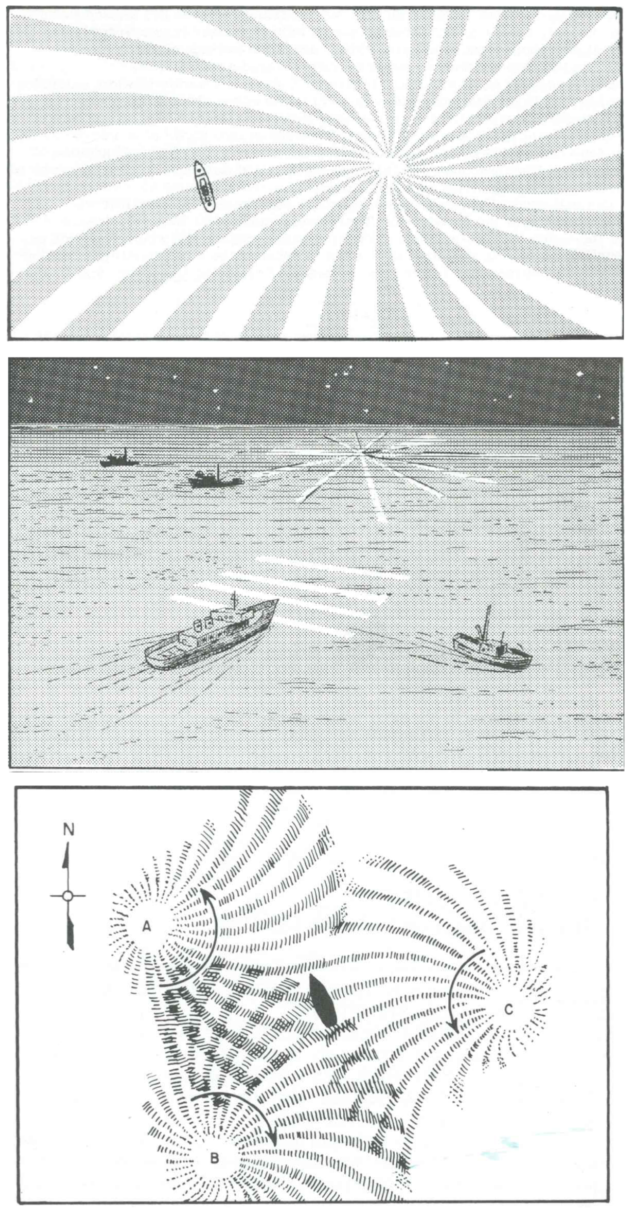


Figure 2: Sketches of light wheels and related phenomena based on several reports (W.R. Corliss 1978)

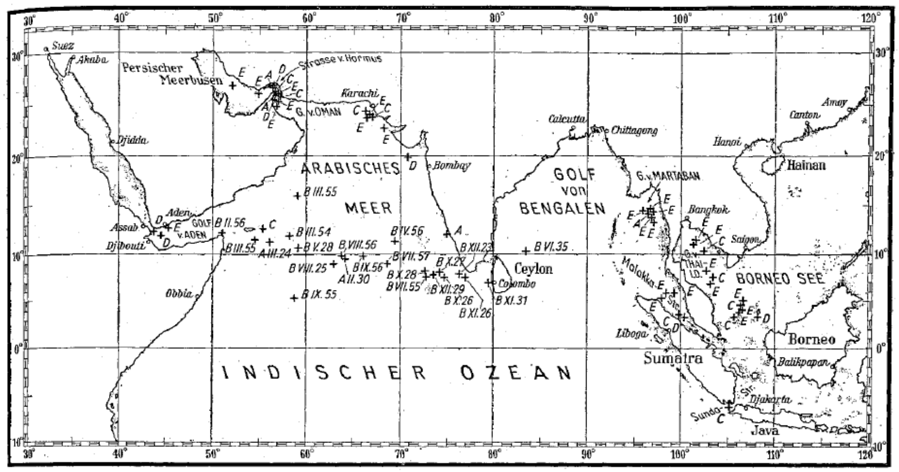


Figure 3: Locations of reports: B indicates a light ball, C through E indicate different versions of the light wheels (Kalle, 1960)

itself, moving along with the ship. As shall be seen later this is very significant and it may be a relevant distinction in some theories. Reportedly, the most striking features of the wheels are that they seem to be perfectly geometric and that their movement is very constant and rhythmic. Inside the wheels brighter and less bright patches have been observed, which seem to brighten when hit by the wheel. As mentioned before, the wheels are observed in a wide range of sizes, but the wheels that are observed in their entirety are typically several tens of metres in diameter. Most reports seem to indicate that the wheels have around 10-20 spokes, though a concrete number is rarely explicitly mentioned. In a few cases the wheels were preceded by parallel light beams shooting past the ship, seemingly at lightning speeds that eventually transformed into said light wheels. A maximum of four wheels of light have been observed simultaneously and all of them have appeared in water shallower than 100 meters.

The reports concerning the light balls are somewhat more uniform. The balls, called patches in most reports, start out with a diameter of about 10 cm and when the balls get close to the surface all balls expand to roughly equal diameters of 50 cm. The moment they hit the surface they seem to explode, by expanding very fast into a disc with a diameter of a few meters to about a hundred meters, after which they disappear in seconds. When observed, there are often many balls at the same time in a large area around the ship.

One common denominator in all the observations cannot be ignored, which is that all of them have taken place in the Indian Ocean and most of them in the Arabian Sea and around Indonesia, as is displayed in figure 3 (Kalle, 1960). This means that it is highly likely that only in this area the right conditions are present for the production of the phenomena. Furthermore, all of the ob-

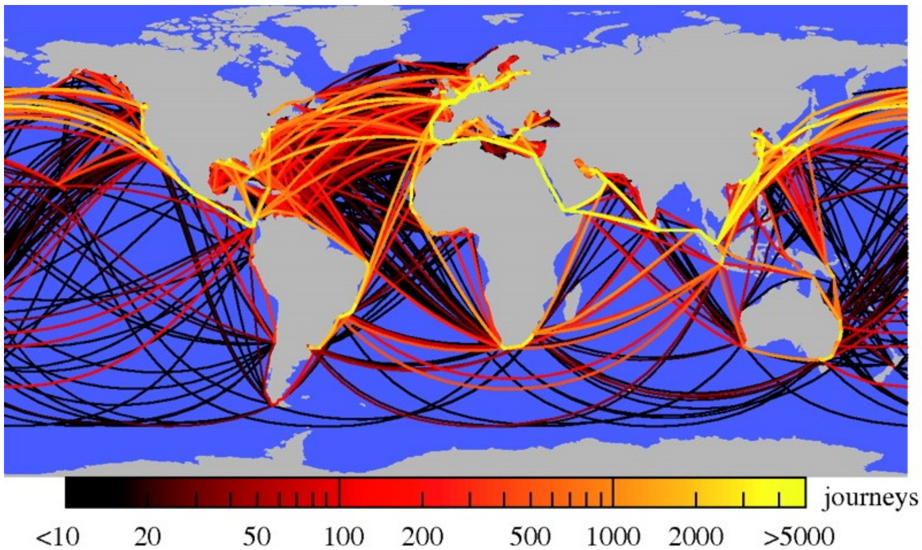


Figure 4: Global ship routes of ships bigger than 10.000 GT in 2007 (Kaluza et al, 2009)

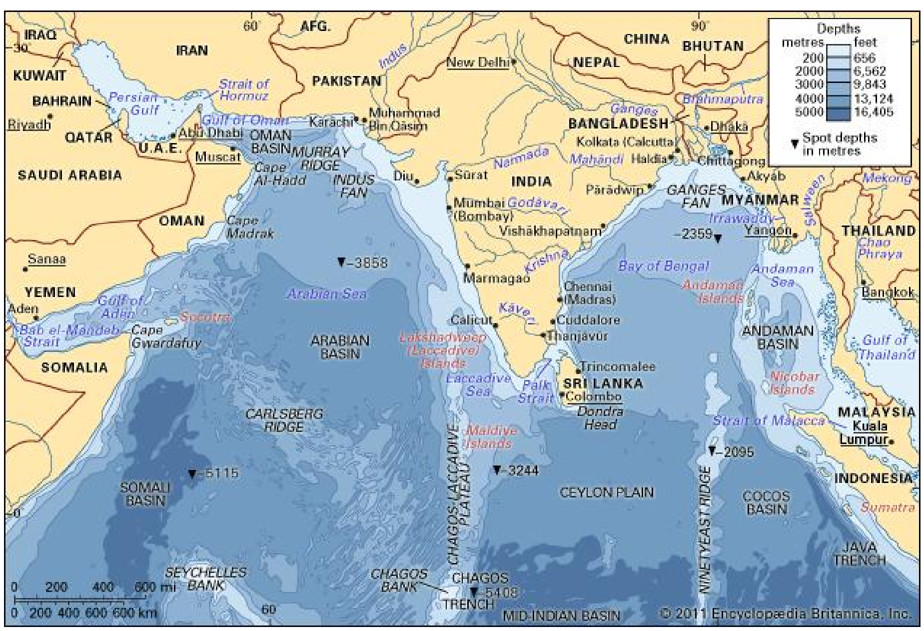


Figure 5: Depth profile of the Arabian Sea and the Bay of Bengal (Encyclopædia Britannica, Inc)

servations of the light balls have been done in water deeper than 500 meters, while observations of the light wheels are mostly restricted to waters shallower than 150 meters. It can therefore not be excluded that we are looking at one phenomenon, but under different conditions. When looking at a map of the locations it seems remarkable that all the observations of the light balls have been done on a line between Aden and Colombo. Furthermore, not visible in the figure but noted in the corresponding article by Kalle (Kalle, 1960), the observations of the light balls roughly move along this line over the year, starting out around February close to Aden and slowly moving eastwards until they are observed nearby Colombo in December. Whereas Kalle uses this as an argument for his seismic theories on the grounds that it approximately follows a tectonic line, but only until about halfway, the more likely explanation is a lot simpler. When looking at a map of the density of global ship routes shown in figure 4 (Kaluza et al., 2010) we see that the line along which the observations take place, overlaps with a density of about 5.000 ships per year, whereas other ship routes through the Arabian Sea only make up a maximum of several hundred ships per year. There are two other routes that are highly travelled, but when we look at the depth profile of the Arabian Sea (figure 5 (Encyclopædia Britannica Inc., 2011)) we see that the route along which the observations of the light balls are made, is the only one through an area with the appropriate depth of more than 500 meters. So assuming the light balls indeed exclusively take place in the Arabian Sea and that they can only take place in deep water, it is merely a consequence that the observations are done along the aforementioned line. This does not exclude a seismological explanation, but it does take away some of the mystery behind the Aden-Colombo line, though it is still not clear why the observations travel eastward over the seasons.

Another common denominator between the reports is the frequency range of the light wheels and beams. From the reports frequencies of the wheels can be determined, which was done for 130 reports(Herring and Horsman, 1985). Of these reports, 121 indicate a frequency between 0.5 $s^{-1}$ and 3 $s^{-1}$, with 96 of those between 1 $s^{-1}$ and 2 $s^{-1}$, the frequency range of the engine revolution in most vessels. This is the frequency with which the individual spokes pass by the ships, in the cases where the centre point of the wheel did not lie on the ship itself. The frequency was chosen as such because it is discussed in the context of the optical explanation, which looks at the beams or spokes as individual waves on the ocean surface. Though this is not further taken into account in this thesis, this data in combination with any data regarding the number of spokes of the wheels can also provide us with the angular frequency of the wheels. The actual number of spokes is scarcely mentioned, but we can derive them from the sketches given in figures 1 and 2. These sketches indicate that a lightwheel has 7 to 28 spokes, which would mean that the angular frequency lies in the range of 0.22 - 1.80 rad/s. Since none of the reports give us much more to work with than that the wheels turn 'fast' or 'very fast', it is useful to keep in mind this actual rotational speed of the turning wheels.

To check if a theory is valid it is also useful to not only look at the specific observations but also at the conditions under which many of the observations took place, which will put some restrictions on any theories. Firstly, the observations have only taken place since the beginning of the 1900's. This means that apparently something changed around this period that enabled the emergence of the observed phenomena. When taking into consideration that all but one of the reports have come from iron ships and that it was in the late 19th century that iron motor ships became more common (Goodwin, 1998), it is very likely that the iron ships are a necessary component in the production of the lights. Moreover, it seems that the amount of observations has drastically decreased over the past twenty to fifty years. Additionally, all observations have either been done in the dark or in the twilight, so the process behind the phenomena has to take place in the dark. The observed lights were very bright and reported to be either phosphorescent green or white. In quite a significant portion of the reports mention is made of how eerily quiescent the ocean's surface seems to be and in none of the reports mention is made of any strong movements in the water. Lastly, the events can take anywhere between five minutes and an hour, with most of them lasting around twenty minutes, so that any phenomenon must be able to last at least for that period.

# 4 Theories

## 4.1 The distinction between theories

Though many theories have been suggested, they do not all exclude one another. Indeed some of the theories cannot stand alone and need another theory to completely explain the phenomena. The most important though not entirely correct distinction here is the one between theories that explain how any light could appear in the ocean and theories that tell us how these lights can be manipulated into the observed patterns. However, it has to be noted that some theories aim to explain both and these have been put in the section for which they look the most promising.

## 4.2 The light source

We will first focus our attention on the source of the lights that appear. Without aiming to find any explanation for the patterns, we will discuss the different ways in which light can be created under the conditions imposed by the observations. This means that the main requirements are that the process can take place in the ocean and that it can create the required brightness. Any other similarities between the observations that it can satisfy are then a bonus, because these either have to be satisfied by these theories, or by the theories that predict the emergence of patterns. The processes that can possibly be responsible for the emission of light in the ocean have been categorized either as those associated with luminescent organisms or as the one associated with earthquakes.

### 4.2.1 Luminescent organisms

The first and most obvious source of light for the phenomena is that of light-emitting organisms, because in many other cases where marine lights were observed without the distinct patterns, it turned out to be marine organisms. Before explicitly looking at light emitted by organisms as a source of the observed lights, we look at the different ways in which organisms can create light. There are three distinctively different ways in which this can happen, categorized by the source of the light emission. Of these three cases, fluorescence, phosphorescence and bioluminescence, this last one is by far the most promising. To clarify why this is the case we will shortly discuss each of them.

#### 4.2.1.1 Fluorescence, phosphorescence and bioluminescence

Firstly, fluorescence requires an organism to have fluorescent pigments. These pigments absorb light, generally from the sun, thereby exciting electrons. When these electrons jump back they emit photons of the wavelength associated with the size of the jump. Fluorescence is not likely to be a source of the observed lights, because it happens very fast, so when the night sets in any fluorescent organisms almost instantly lose their luminescence. Secondly, phosphorescence is very similar to fluorescence in that it needs a source of light to initially excite its electrons, before they can fall back and emit photons. However, in phosphorescence the electrons are more stable in their excited states and take a while to fall back to their ground states. Though this makes them a candidate for the phenomena, it does bring up the question how the emitted lights come to be so bright, because the standard emission by phosphorescence is very gradual. This means that the phosphorescent organisms need to be triggered by some mechanism which causes a lot of electrons to jump back at the same time, for example by seismic or ship waves, but it has never been proven that this is possible, in contrast with bioluminescence. This brings us to bioluminescence, where the source of the light is in the food consumed by organisms, namely the protein categorized as luciferin. When luciferin is oxidized it yields carbon dioxide and excited ketones, which release their energies by emitting photons and therefore light (Hanley III, 2011). This reaction needs the enzyme luciferase as a catalyst, which the luminescent organisms possess in one form or another. Both luciferin and luciferase are names for the group of varying proteins and enzymes different organisms use in their production of light. The light produced by this process is generally bluish, because this is the color that reaches the furthest in the water and has therefore been evolutionary preferable.

#### 4.2.1.2 Bioluminescent organisms

Bioluminescence has evolved independently many times and can therefore take many forms in organisms ranging from phytoplankton to squids. To see why biolumiscence is the most promising of the three luminescences, we will only need to look at two of these: Bacteria and dinoflagellates. This is because they are the organisms that display a type of bioluminescence we are interested in on the locations we are interested in. This type of marine bioluminescence namely has two important features: The flashes need to be bright but short, or the wheels and balls wouldn't be able to move so fast and the organisms should not be so big that they can be discerned by the observer as individual light sources, or this feature would have appeared in some of the reports.

Those bacteria that are bioluminescent only are so in groups, because this is necessary for them to produce luciferase. This is the case because the bacteria continuously check how many other bacteria are around through the emission of an auto-regulator, called the lux auto-inducer. When there is a low density of bacteria this auto-inducer will simply diffuse out of the cells and nothing happens. However when many bacteria are producing the auto-inducer packed together, the density of lux rises and at a critical concentration this triggers the production of luciferase in all of the bacteria. (Hastings and Nealson, 1977) These bacteria thus appear in glowing colonies, without flashing all too much.

Dinoflagellates are a type of unicellular protists and are mainly marine plankton, but some variations live in fresh water. Only a part of all dinoflagellates are bioluminescent and these are generally known for their appearance as bright colonies around ships or along coasts. A lot of lab research has gone into studying dinoflagellates and under these lab conditions they have been found to flash very bright when subject to shear turbulence, which can for example be caused by ship waves. There are several reasons why dinoflagellates are the most viable option to explain the diverse phenomena discussed earlier. One of the most obvious reasons is that dinoflagellates have a strong circadian rhythm, so that they only emit light when it's dark, which could explain that all observations have been done in the dark. Additionally, different types of dinoflagellates can have strongly different morphology, such as being armoured (thecae) or not and having spines or not. This causes them to display a wide range of variations in their reaction to their surroundings. Therefore it is very probable that a variation exists with the properties that are needed in our explanation, such as a convenient trigger threshold for bioluminescence. Dinoflagellates are also known for their bright emission that can be triggered by different pertubations to its surroundings, which makes it very attractive for some of the theories proposed in section 4.3. Lastly, it has been shown that dinoflagellate concentrations will decrease when the water becomes polluted (Sætre et al., 1997). Seeing as how the Arabian Sea and the land and marginal seas bordering it are home to much oil drilling and oil spills, among which the Gulf War oil spill, one of the largest oil spills in human history (Edwards, 1992), it could be that over the past few decades dinoflagellate concentrations have decreased. This could explain the reduced number of observations of the light wheels and light balls over the past few decades, making bioluminescent dinoflagellates even likelier candidates as a source for the lights. For these reasons only dinoflagellates will be discussed more extensively.

#### 4.2.1.3 Dinoflagellates as the source of the lights

If the bioluminescent dinoflagellates are indeed the source of the lights they need an external source to trigger them in the required patterns, since there is no indication they can display these patterns on their own. Therefore it will prove useful to study the exact requirements for the triggering of bioluminescence in dinoflagellates. Dinoflagellates are generally triggered by changes in their surroundings, such as movement of water or changes in pressure. However, should all flow of water trigger bioluminescence, then dinoflagellates in the ocean would constantly emit light, because the ocean is never completely at rest. Obviously, this is not the case and it turns out that the trigger of bioluminescence is actually a rapid and preferably big change in the flow of water around it, so that only objects big enough to disturb the ambient flow of the ocean, like predators and ships, can trigger it. Therefore, research regarding this trigger mechanism has mainly focused on thresholds involving the magnitude and rate of change in the water surrounding dinoflagellates.

That determining these threshold values is not straightforward can be seen when comparing findings of Latz et al. that constant laminar flow of $0.06 - 0.3\,\mathrm{Nm}^{-2}$ triggers bioluminescence (Latz et al., 1994), with those of Cussatlegras et al. that only changes in this flow trigger bioluminescence (Cussatlegras and Le Gal, 2004). By combining their findings with other research it becomes clear that even though it is debatable whether sufficient stationary flow can trigger a weak bioluminescent response (Latz et al., 2004; Maldonado and Latz, 2007), changes in the flow definitely trigger a stronger bioluminescent response at lower thresholds (Anderson et al., 1988). These changes can be induced by subjecting dinoflagellates to a turbulent flow, which is by definition constantly changing, or by a laminar flow with for example oscillating shear (Blaser et al., 2002). The threshold value for shear flow to trigger biolumiscence has been determined in some experiments by introducing an instantaneous start of a shear flow, which tells something about the magnitude a change should have to trigger bioluminescence. The threshold value varies between different types of dinoflagellates and was found to be $0.70 \pm 0.27\,\mathrm{Nm}^{-2}$ for pyrocystis noctulica (Cussatlegras et al., 2005) and around $0.6\,\mathrm{Nm}^{-2}$ for pyrocystis fusiformis (Blaser et al., 2002).

All experiments regarding pressure changes have been done by changing the pressure of the entire fluid in which the dinoflagellates are placed. Anderson et al. found that pressure changes of 0.05-0.5 bar/s in a pressure chamber did not trigger bioluminescence and that only changes greater than 2 bar/s triggered bioluminescence (Anderson et al., 1988). Even then the bioluminescence was only triggered at the edges of the fluids, especially at the surface, so that maybe other effects than purely pressure are in play, because dinoflagellates in the bulk of the fluid also experienced the pressure changes. Watanabe and Tanaka (Watanabe and Tanaka, 2011) studied the impact of shockwaves on pyrocystis lunula by dropping a mass on top of a cylinder which created an instant shock wave in the fluids. Though no quantitative data was obtained for the pressure threshold, they did find that even their lowest pressure change of around 1 bar already triggered some response and that the response increased for bigger pressure changes. This indicates that this type of shock wave triggers a stronger response than a gradual change of pressure as done by Anderson. Furthermore, they found that bioluminescence was triggered in their entire fluid, though still stronger at the edges. Since most research is focused on the triggering of dinoflagellates by natural circumstances like predators and ships, this is the only data available on pressure changes.

Since all events have taken place in or around the Arabian Sea, it is instructive to look at the biodiversity of the Arabian Sea, because if the lights are indeed caused by dinoflagellates, they should live there. The Arabian Sea has quite a rich diversity in phytoplankton, among which 130 of the 452 known species of dinoflagellates, whose diversity declines westwards to about 88 species in the Red Sea (Chiffings, 1995). Especially in the Gulf of Aden, one of the areas with a lot of sightings, high densities of phytoplankton are found. Among the dinoflagellates found in these areas are also a few of the more common bioluminescent ones, such as variations of the pyrocystis and noctulica strains (Lapota et al., 1988). Since bioluminescent dinoflagellates are found in many waters all around the world, they cannot explain why the observations exclusively take place around the Arabian Sea, but the fact that they are found there does indicate that they could play an integral part in the final theory on marine lightwheels and lightballs.

### 4.2.2 Earthquake Lights

A different source of the emission of the light could be earthquakes themselves. Since the 1500's reports have been made on the observations of bright, white lights that precede earthquakes (Derr, 1973). Recently more reliable reports have been made, where several eyewitnesses confirm each other's stories and even camera footage exists where the lights are seen (Heraud and Lira, 2011; Yasui, 1968), as shown in figures 6 and 7. Both photographs are taken from a larger collection of photographic evidence of earthquake lights (EQL) (Yasui, 1968). All this evidence strongly supports the existence of EQL, even though the exact mechanism behind it is not clear. To complicate the efforts to find a satisfactory explanation, the EQL do not always take the same form and a distinction between six different types of EQL can be made, of which the most prominent are seismic lightning, luminous bands in the atmosphere (reminiscent of the auroras discussed in section 4.4) and incandescent globes (reminiscent of the ball lightning discussed in section 4.5) (Derr et al., 2011). However, it has been shown under controlled conditions in laboratories that the squeezing of certain types of rock can generate electric fields (Freund et al., 2009). Though it is still a step away from explaining any lights, accelerating charged particles do emit electromagnetic radiation, which is carried by photons, so should photons of the visible wavelength be emitted, this squeezing of rocks can indeed create lights.

The observations of the EQL are in agreement with many of the reports on the marine lights, in that they are bright and white. Furthermore, a significant amount of the wheels were observed to be above the water and though this could indeed be due to optical illusion, the lighting by electromagnetic fields could actually reach above the water. However, it is unlikely that the lights are the cause of all the marine lights, because generally all observations of EQL have

Figure 6: Photograph of earthquake lights near Mt. Saijo, Japan, taken on February 12, 1966 (Yasui, 1968)

Figure 7: Photograph of earthquake lights in the area around Mt. Kimyo, taken on September 26, 1966 (Yasui, 1968)

been done during earthquakes stronger than $M_W = 6.0$. Only 5 earthquakes of that magnitude have occurred in the Arabian Sea in the time frame 1905-2005 (Rafi, 2005), which is approximately the period that the marine lights were observed. It could be possible that the threshold is somewhat lower than 6.0, but even then it is highly unlikely that there were enough earthquakes to cover all observations, seeing as how they amount to over a hundred in total, especially when taking into account that apparently not all earthquakes lead to EQL.

## 4.3 The patterns

The theories discussed in this section are less complete and more speculative than the theories involving the creation of marine lights without patters. None of theories that have been offered for the patterns are by any means complete. Some can only approach the shape of the observed patterns, others need additional elements for the complete explanation of them, besides a source of the lights. The explanation of any patterns is further complicated by the fact that maybe not all observations really took place. For example, observations have been made of both white and phosphorescent lights, but every theory discards one of the colors by stating it was probably wrongly observed due to the suddenness and brightness of the phenomena. This seems like quite a reasonable assumption, but the problem is that the same argument can be held for a lot of the observations, but is only done for a few. Because different theories look at different aspects of the observations, it can also be that more than one theory seems valid. This analysis is aimed at giving a clear view of the theories with their strong points, but also the points where they either need more work, or where they seem to fail completely.

### 4.3.1 Waves from earthquakes

When looking at the locations of the observations, it is striking that they all appear in the Indian Ocean, which is a seismically active area. This indicates that there could be a seismological cause for the phenomenon. Such a theory has indeed been offered by Kalle (Kalle, 1960), who looks at the observed lights as a result of the triggering of phytoplankton by seismic waves, so that any pattern that is observed is just seismic waves made visible by the phytoplankton. Before we look at the validity of his theory, a short discussion of seismic waves in water is in order. Seismic waves come in different forms and can generally be categorized as primary body waves, secondary body waves and surface waves. Since surface waves are only found on the surface between two different media and Kalles theory only concerns waves travelling through a body of water we will not discuss these any further. Additionally, the secondary body waves cannot travel through viscous media such as water. This is because they are transversal waves and they therefore need an elastic medium to propagate through. Because liquids are very inelastic, any secondary waves running into water will quickly dissipate. That leaves primary body waves (P-waves), which are longitudinal pressure waves, identical to sound waves. They arise due to a push to a medium, thus creating a pressure wave that travels through the medium. (Shearer, 2009)

Now that we know what the waves in Kalle's theory should look like, we can test its validity. The theory is split in two parts, namely seismic waves in deep and in shallow water. He states that in deep waters the waves caused by the earthquakes will travel to the surface, namely in the form of the small balls. At the surface the waves will quickly expand due to the transition to air, thus losing their energy and disappearing. If these waves would be able to trigger bioluminescence, it would lead to the observed light balls. In deep enough water you would only need a single source for the different balls, since slight deviations in the angles in which they are emitted can cause quite big displacements on the surface between the different waves, without the observer noticing that the balls travel under different angles. This explanation makes sense, but there are a few obscurities in it that cannot so easily be dismissed. Firstly, P-waves travelling through water do so at a speed of 1500 m/s. However, reports indicate that it was possible to see the light balls rising up from the depths, whereas balls travelling at speeds of 1500 m/s would almost instantly reach the surface. There are no real measurements done on the velocity of the balls and so it could be they were actually travelling at this high speed, but any rough estimates made from the reports would indicate a travelling time of at least several seconds to the surface. Since most observations are done in water of a depth between 500 and 2.000 meters, this would indicate a speed of 150-500 m/s and that is assuming the balls are visible from the very beginning of their ascent. The exact depth beyond which no light can be observed depends on the brightness of the light, but since only around 1 % of light will reach further than 200 meters in water, it is a safe assumption that the balls can only be seen when they are closer to the surface than these 200 meters. Additionally, dinoflagellate concentrations are highest close to the surface. This means an estimate of the observed speed of the light balls should lie even lower, with a maximum of around 70 m/s.

The next obstacle in this theory is that the pressure perturbations of the P-waves should be sufficient to trigger biolumiscence. As has been discussed earlier, the exact threshold of dinoflagellates regarding shock waves has not been extensively studied. The studies from which data was taken did however indicate that the changes need to be significant compared to the ambient pressure, which at sea level amounts to 1 bar and quickly increases with depth. Little data is available on the pressure changes accompanying P-waves, but we do know that the corresponding displacement of water should not be too strong, because the surface of the ocean in nearly all observations was reported to be quiescent. We will therefore look at this displacement and see if it is of a magnitude that should have been noticed by the observer.

$$\xi = \frac{p}{Z_0 \omega}. \tag{1}$$

$$Z_0 = \rho v_{sound}. \tag{2}$$

To do this we use equation (1), where $\xi$ is the particle displacement, $p$ the wave pressure, $Z_0$ the acoustic impedance of the medium and $\omega$ the angular frequency of the wave. The acoustic impedance is given by equation (2). Though dependent on salinity, temperature and pressure, the speed of sound in water is around 1500 m/s and the density of water is around 1.000 $\mathrm{kg\,m^{-3}}$. This gives an acoustic impedance of $1.5 \cdot 10^6$ Pa s/m. If we have a pressure change of 5 % of ambient pressure and a seismic wave with a frequency of 1-20 Hz, then this gives us a particle displacement of .2-3 millimetres. Even if the sea is quiescent at the time such a displacement takes place, it is unlikely that in the middle of so much light a displacement of a few millimetres would be noted. Earlier it became clear that the trigger treshold of dinoflagellates may lie around a few bar per second. That would give displacements on the order of a decimetre, which could perhaps be observed. However, even if the pressure changes involving P-waves are smaller than a bar, the pressure changes induced by pressure waves are extremely fast, so if the rate of change is the important parameter, then pressure waves do not need to be on the order of a few bar to trigger bioluminescence.

In this theory it is very important to see what the behaviour of P-waves is at the ocean surface, because the observations indicate a quick dissipation of the waves over the ocean surface. Sadly, the behaviour of P-waves in water and on the interface between different media was too complex to study and understand completely in the amount of time that was available. However, the strength of reflection at an interface is generally dependent on the difference in acoustic impedance between the two media. The reflection coefficient at normal incidence is given by by equation 3 and shows us a more exact relation.

$$R = \frac{(Z_1 - Z_0)^2}{(Z_1 + Z_0)^2)}. \tag{3}$$

This relation shows that a large difference in impedances would also result in a large reflection coefficient. When putting in typical values for the acoustic impedances of water and air the corresponding reflection coefficient is 99.94 %. This has several consequences: Firstly, the waves would indeed not splash, since they are almost completely reflected. On the other hand this does offer the question why the balls would explode on the surface and not simply turn back causing a light trail on the way down. To truly determine how satisfactory the seismic waves are as a cause of the light balls it is therefore important to determine what happens at the ocean surface to a P-wave.

How seismic waves could lead to the lightwheels can be understood when we look at the earthquakes as circular waves originating from a point source. When hitting the ocean surface, the waves will partially reflect, but if the water is sufficiently shallow the waves can reflect back from the bottom upwards

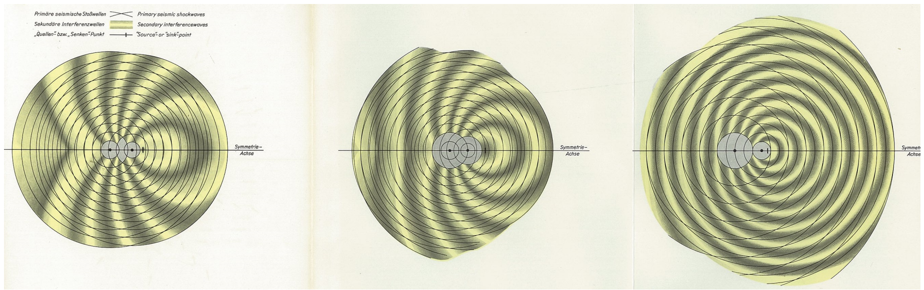


Figure 8: Interference pattern of two circular point sources with varying ratio's in wavelength and velocity. From left to right these ratios are: 10:9, 10:8, 10:5 (Kalle, 1960)

again. When the water is shallow enough this can occur several times, creating a pattern of radially increasing circles. When two of these point sources are placed close together the patterns will interfere and depending on the distance between the sources and the wave speeds and lengths originating from the source, a pattern similar to a wheel with curved spokes can appear (see figure 8 (Kalle, 1960)). The turning of the wheels could then be a result of changing wave velocities and wave lengths of the two sources, thereby making a slightly different wheel, which can appear as a turning of the wheel. At certain differences in wave speed between the two point sources the appearing pattern will resemble parallel light beams, thus explaining the observed transition between parallel light beams and the lightwheels.

There are several assumptions in this theory that need further explanation, but do not get it. To start off, Kalle makes his theory attractive by proposing that the wheels and balls are both consequences of the same phenomenon, namely earthquakes. However it now turns out that for the different patterns he needs different types of sources. For the light balls he needs a source emitting longitudinal pressure waves, which seems valid, but for the lightwheels he needs a point source emitting circular waves. He gives no indication as to why the waves would become circular, while it is not evident why this would be the case: a circular wave would be more typical for an S-wave, which cannot propagate in water. Moreover a significant portion of the waves has to be reflected from the surface to enable the emergence of at least a few concentric circles. It has been shown that this might well be possible, but then this should also be the case for the waves causing light balls. This contradicts the reports on the light balls, however, because they would not explode, but simply reflect. This has not been observed to be the case in any report, implicating the waves causing the different phenomena would also vary in their reflectivity. In addition to these arguments, the waves that are proposed do not cause the observed patterns, but wheels with spokes curved along a symmetry axis (figure 8), which is quite different from the observed wheels. Should these point sources be the cause of the wheels, then the observed movement would also not be very rhythmic, whereas most reports indicate that it should be. Kalle puts all this down to biased observations, but since the observations provide the only real data for any theory, it seems a bit blunt to dismiss two aspects which comes back in nearly every single report so easily. To top it all off, should two point sources lie at the cause of the emergence of lightwheels, then it seems statistically improbable that this would happen a lot, since no indication is given as to why two point sources would occur close together. Instead, one would expect that for every single report of a light wheel, a lot more reports on simple radially increasing circles should be done, because that is what would happen if just one point source would appear. Even though some reports do tell us that these patterns also take place, they are actually a minority and most reports are done on lightwheels. This would mean that for some reason it is very probable that two of these point sources emerge so close together, though no indication as to why this would be the case was found in this theory, or any other geological literature.

In conclusion, Kalle has not found a single explanation for both phenomena, but separate explanations for both the balls and the wheels. When we look at the aspects in which they vary, we can conclude that his explanation for the light balls is the most promising of the two, especially since there is no indication the waves he proposes for the wheels are even possible. This leaves us with both the inconsistency between observed and theoretical speeds and the reflectivity problem, because the reflectivity should be a lot lower than the one found in our estimations. However, as mentioned before the physics involving seismic waves are a lot more complex than our estimations make them out to be and it could be possible that delving deeper into this subject will provide us with more pleasing results. Additionally, this is the only theory involving light balls, so even though it seems flawed, further analysis of the theory could really be worth the effort.

### 4.3.2 An optical explanation

The second theory involving patterns does not offer explanations for the lighting up of the water, but does show that if there is lighting up of the ocean in parallel moving light beams, optical illusion could explain some of the observed patterns. The basis for this theory was first proposed by Tydeman (Tydeman, 1911, 1921) and later expanded on by Verploegh (Verploegh, 1968). The basic concept underlying their theory is that the observed patterns can partially be explained when the perspective of the observer on the ship is closely examined. When parallel light beams would reach up all the way from the ship to the horizon, then the farther away they are, the smaller they seem due to his perspective. Normally you could see this is caused by perspective, because you have some frame of reference thanks to your surroundings. However on the ocean and especially in the dark there is no such thing and distances are extremely hard to estimate. This could lead to large errors in the estimates of the observer and where he thinks he sees a wheel with its origin on the horizon, he is actually looking at parallel light beams reaching up to the horizon. The

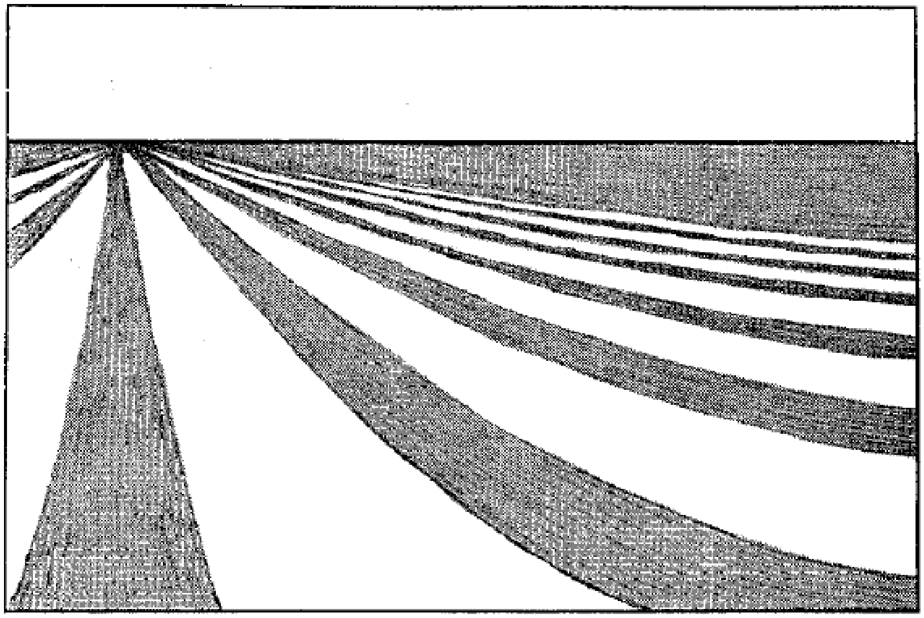

Figure 9: Pattern that is observed when an observer on a ship looks at parallel light beams (Verploegh, 1968)

parallel beams as seen from the perspective of an observer on a ship is displayed in figure reffig:opticwheel (Verploegh, 1968), which is actually the result of calculations involving the viewpoint of this observer rather than just a sketch. The extreme speeds of the parallel light beams shooting over the ship can also be caused by perspective, because the closer they get, the faster they appear to move. This is more commonly observed when looking at the beams of a lighthouse. In this situation the effect would be even stronger, since this effect is enhanced if the height difference between the observer and the lights is smaller and the height difference here is obviously smaller than that for a lighthouse and the average observer. This also has other consequences for the estimates of the observer, because if he assumes the light beams move constantly at the speed they seem to have when shooting past the ship, then he will greatly overestimate the distance over which they travel. The final observation that the wheels are turning can be explained by a parallax in the observations that changes as the ship moves. This causes a rotation dependent on the angle under which the observer is looking at the beams and the angle they make with the horizon, as well as on the height and speed of the observer.

All these effects combined could lead to curved wheels, rhythmically turning with their center point on the horizon. Whether this is really the case in the observed cases is hard to judge, because not all data to check if the conditions required for the theory to be viable is documented in all of the reports, for example the speed of the ship and the angle of incidence of the rays are seldom mentioned. On at least one occasion however, an observation of such a lightwheel led the observer to go up the mizzen's top, where, probably due to the increased height difference he unintentionally created, he saw that the spokes were actually parallel light beams travelling towards the ships and that any observed wheel was merely an optical illusion. (Corliss, 1977) This is a strong indication that this theory could explain any lightwheels turning with a center point on the horizon. It still leaves two questions unanswered: Where do the parallel light beams come from and what is happening in the cases that the center points were clearly discernible? The answer to the first question is still uncertain, though there does exist a theory for the appearance of parallel rays (Tydeman, 1921). Should the ocean surface be rippled and not completely quiescent, then these rippling waves can act as lenses for a light source underneath the water and should this light source be uniform across a large area, this could result in the appearance of parallel light beams moving along with the waves. Though there is no reason why the formation of parallel beams couldn't be caused by this mechanism, there has also been no proof that it can be the cause. However, should it prove to be a correct explanation, then the combination of these optical theories would reduce the problem from explaining the appearance of giant rotating wheels, to finding a source that could uniformly emit light across a large area of the ocean, which should be a lot easier. Phosphorescence could for example be a very viable light source to explain such a large scale, homogeneous emission. The second question remains unanswered, which encourages us to look at other theories.

#### 4.3.3 Waves caused by a magnetic field

Here I would like to offer a new explanation for the wheels that are centred on a ship, using movements or tensions in the water caused by the ship's magnetic field. Because the Lorentz force works in quite the same way as the Coriolis force, namely perpendicular to the direction of movement, and the Coriolis force has been known to create flow patterns with curved spokes, so-called amphidromic points, it is interesting to at least see if a magnetic theory could in some way be possible. Clearly the main requirement here is that a ship generates a magnetic field in the first place. Since the observations have been done during the time that iron ships were used, the ships from which observations were done indeed generated a magnetic field. The iron in ships namely has a combination of an almost permanent magnetization and a temporary magnetization induced by the Earth's magnetic field. The permanent magnetization is created when iron is heated above its Curie point, after which the magnetic dipoles in the iron align to the field that is in place during the cooling process, which would in this case probably be the Earth's magnetic field. Since the Curie point for iron lies below its melting temperature, this process takes place during the construction of the ships. Generally the permanent magnetization of the ship as a whole will not have a strong single direction, since not all parts of the ship are cooled down at the same time lying in the same direction. The temporary field that is induced by the Earth's magnetic field follows from the large difference in magnetic permeability between iron and the surrounding water and air. Since the magnetic permeability of the ship is a lot higher, the field intensity in the ship is increased and therefore there will be an anomaly in the magnetic field around the ship. These effects have been studied for the ship the Discovery II and part of the results are displayed figure 10 (Bullard and Mason, 1961), where the individual points are measurements done and the line shows the theoretical fit, based on the previously mentioned permanent and temporary magnetization components. This gives some indication of what the magnetic field for different headings of the ship looks like. These results indicate that the magnetic field caused by a ship is on the order of several hundred nanotesla. When comparing this to the Earth's magnetic field, which varies between 25 and 65 microtesla, it may seem weak but we will later show that it is definitely not insignificant.

Interestingly, this magnetic field of ships has been used in wars as a trigger for sea mines. Therefore, even though relatively little research has been done as to the exact origin of the magnetic field, a lot of innovations have been done to suppress this magnetic field, so-called degaussing. Sea mines with magnetic triggers were first used in World War II, but because the processes involved in degaussing were very expensive, development of useful degaussing methods has been quite slow. These developments could be involved in the reduced number of observations, though that is unlikely because degaussing still requires a lot of effort and is still quite expensive, which makes it improbable that any ships but war ships are degaussed.

For a magnetic field to induce movement in the water, the ocean must have some electric charges. This is of course the case, because, depending on the ocean's salinity, there is a certain amount of ions present in any salt water. The net charge of the ocean is zero due to the positive and negative ions cancelling each other out, but charges of those ions in the water are quite significant. We will assume the Arabian sea has an average salinity of about 37 ‰, which is quite high, but since we will only look at lightwheels here we can assume we are looking at shallow waters. These generally have a higher salinity due to high evaporation compared to volume. Another reason the estimate might be off is that the Arabian Sea has quite a strong seasonal variation in salinity of a few ‰. However, for our crude calculations a salinity of 37 ‰will suffice.

To determine what this means for the charges in the water we look at a typical distribution of ions, given in figure 11 (Grobe, 2007) and calculate what positive charge this gives for 1 kg of sea water, since the negative charge will be equal but opposite to this value. The resulting value is approximately 61.500 Coulomb. To see if this value in combination with a field of one microtesla can cause any significant movement in 1 kg of water, we neglect the sea's movement and assume the ship moves at 10 m/s.

$$F_L = Q(E + (v \times B)) \tag{4}$$

The maximum resulting Lorentz force then follows from equation (4): $F_L = QvB = 0.62\,\text{N}$ and this gives us an acceleration of the water of 0.62 $\text{ms}^{-2}$. Of course there will be no net movement in the water, because the negative charges

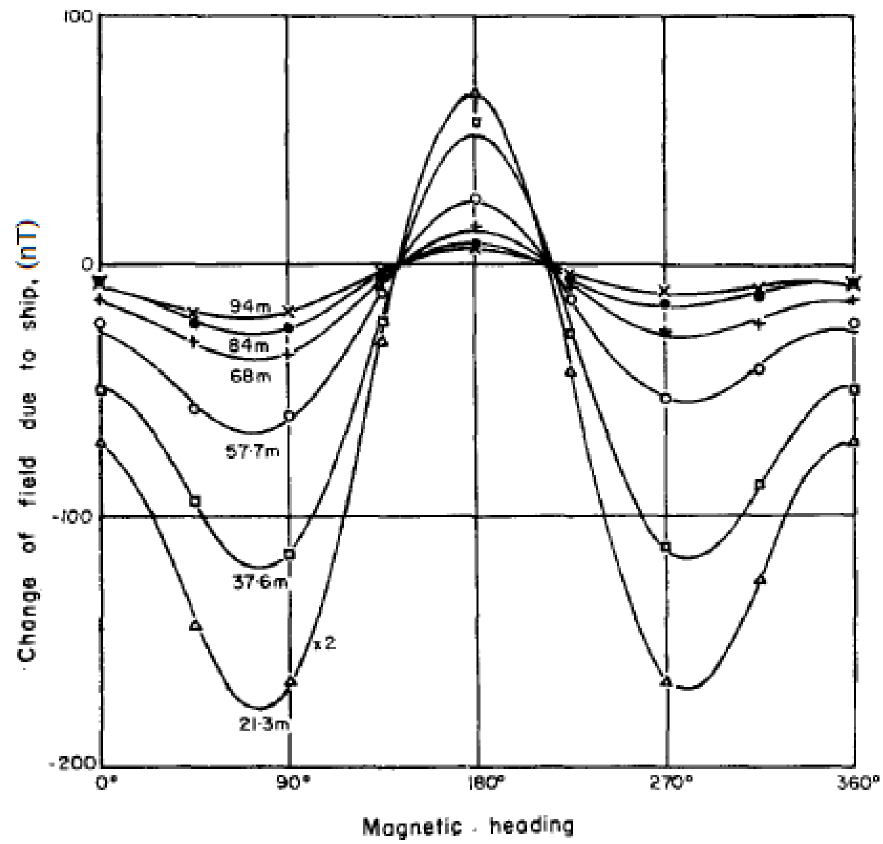


Figure 10: Disturbance of the field around the Discovery II as a function of course and the distance astern. (Bullard, 1960)

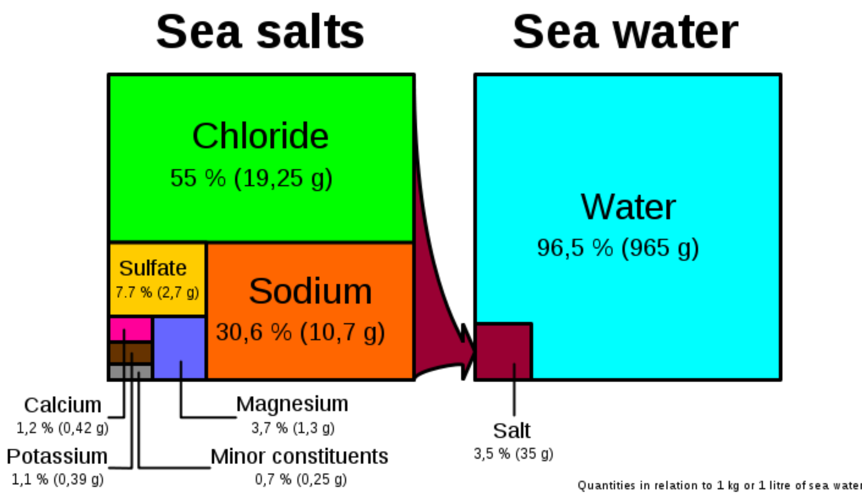


Figure 11: Typical ion distribution in sea salt (Grobe, 2009)

will cause exactly the same acceleration in the opposite direction. However, what this could create is stress in the water, caused by moving ions pressing against the water molecules, which could cause bioluminescence. Aside from this effect, since we are looking at accelerating charges here, the resulting electromagnetic radiation could produce photons, possibly of a visible wavelength. Though that is quite some jumping to conclusions, what we have shown is that the field caused by a ship can create significant tension in the water, which could result in light in a number of ways.

Since these first estimates indicate that the forces involved in the magnetic field of a ship could create significant tension and movements, it is useful to look at the flow pattern that results from such a magnetic field. To make an analytical approach possible, a strong simplification of the real situation will be studied, in order to see whether the results look promising enough to encourage further analysis. For the analytical approach we treat the ship as a cylinder parallel to and centred on the z-axis with height $H$ and radius $R$, where the z-axis is chosen anti-parallel to gravity and scaled from 0 to 1 on respectively the ocean surface and the ocean bottom. The magnetic field B we will look at is parallel to the z-axis and the water is treated as an inviscid fluid. The linearized equations governing these kind of perturbations are:

$$\rho\dot{\vec{u}} - \vec{j} \times \vec{B} = -\nabla p. \tag{5}$$

Here $\vec{j}$ denotes the current density, given by:

$$\vec{j} = \sigma_p \vec{u}_p + \sigma_n \vec{u}_n. \tag{6}$$

Positive and negative ions are denoted by subscript $p$ and $n$ respectively and $\sigma$ and $\vec{u}$ denote the charge density and the velocity of the ions. The mean material velocity $u$ is defined as:

$$\vec{u} = \frac{1}{\rho}(\rho_n \vec{u}_n + \rho_p \vec{u}_p). \tag{7}$$

We can also state that the divergence of $u$ is 0, by assuming that water is incompressible, which is very close to the real situation, and that the sea water as a whole is neutrally charged:

$$\vec{\nabla} \cdot \vec{u} = 0. \tag{8}$$

In these equations $\rho$ is the mass density of the ions. To start off, we will treat the ocean water as a mix of positive and negative ions, to study the general flow pattern that arises. If the outcome looks promising we will try to include the water molecules in some way.

We introduce the reduced pressure $p_{red}$, which is the deviation from the hydrostatic pressure. In our first approach we neglect movement of one of the charge carriers, in this case the positive ions, so that $\vec{u}_p = 0$ is zero. These assumptions allow us to make the following simplifications:

$$\vec{j} = \sigma_n \vec{u}_n \tag{9}$$

$$\vec{u} = \frac{\rho_n}{\rho} \vec{u}_n \tag{10}$$

Since we know B is parallel to the z-axis, the crossproduct with $\vec{u}$ is now easily rewritten and equation (5) can be split up in the following equations:

$$\rho_n \dot{u}_n - B\sigma_n v_n = -\frac{\partial p_{red}}{\partial x}, \tag{11}$$

$$\rho_n \dot{v}_n + B\sigma_n u_n = -\frac{\partial p_{red}}{\partial y}, \tag{12}$$

$$\rho_n \dot{w}_n = -\frac{\partial p_{red}}{\partial z}. \tag{13}$$

Here $u$, $v$ and $w$ are respectively the velocities in the x, y and z direction. Equation (8) can also be written in terms of $\vec{u}_n$:

$$\vec{\nabla} \cdot \vec{u} = \frac{\rho}{\rho_n} \vec{\nabla} \cdot \vec{u_n} = 0. \tag{14}$$

Since $\frac{\rho}{\rho_n}$ is simply a constant, the divergence of $\vec{u}_n$ should also be zero, so that our final equation becomes:

$$\frac{\partial u_n}{\partial x} + \frac{\partial v_n}{\partial y} + \frac{\partial w_n}{\partial z} = 0. \tag{15}$$

Since our ship is assumed to be cylinder-shaped and centred on the z-axis, it will prove useful to rewrite our system of equations in cylindrical coordinates $r$, $\phi$ and $z$, where the radial, azimuthal and vertical velocity components are expressed by $u_r$, $u_\phi$ and $u_z$ respectively. Doing so gives us:

$$\rho_n \dot{u}_r - \sigma_n B u_\phi = -\frac{\partial p_{red}}{\partial r}, \tag{16}$$

$$\rho_n \dot{u}_\phi + \sigma_n B u_r = -\frac{1}{r}\frac{\partial p_{red}}{\partial \phi}, \tag{17}$$

$$\rho_n \dot{u}_z = -\frac{\partial p_{red}}{\partial z}, \tag{18}$$

$$\vec{\nabla} \cdot \vec{u} = \frac{1}{r}\frac{\partial}{\partial r}(r u_r) + \frac{1}{r}\frac{\partial}{\partial \phi}(u_\phi) + \frac{\partial}{\partial z}(u_z) = 0. \tag{19}$$

Now we will try to find a solution of the form

$$p_{red} = \sum_{n,m} P_{n,m}(r) e^{i(m\phi - \omega t)} cos(2n\pi z). \tag{20}$$

The solution should have this z dependence so that $u_z$ is zero both at the $z = 0$ and at $z = 1$, the surface and the bottom of the ocean. In order to find it we need a differential equation for $p_{red}$. Therefore we will write equations (16), (17) and (18) in such a way that we can use them as input for equation (19). To make the expressions somewhat simpler we will rescale both $p_{red}$ and $t$ by introducing $p_{red,*} = \frac{1}{\sigma_n B} p_{red}$ and $t_* = \frac{\sigma_n B}{\rho_n} t$. With these substitutions the equations change into:

$$\frac{\partial u_r}{\partial t_*} - u_\phi = -\frac{\partial p_{red,*}}{\partial r}, \tag{21}$$

$$\frac{\partial u_\phi}{\partial t_*} + u_r = -\frac{1}{r}\frac{\partial p_{red,*}}{\partial \phi}, \tag{22}$$

$$\frac{\partial u_z}{\partial t_*} = -\frac{\partial p_{red,*}}{\partial z}. \tag{23}$$

To solve these equations we assume the waves are monochromatic and proportional to to $e^{-i\omega t}$. Because of our rescaling we will use the notation $e^{-i\omega_* t_*}$, where $\omega_* = \frac{\rho_n}{\sigma_n B}\omega$. Combining these equations with (19) allows us to derive the aforementioned differential equation for $p_{red,*}$:

$$\frac{\partial^2 p_{red,*}}{\partial r^2} + \frac{1}{r}\frac{\partial p_{red,*}}{\partial r} + \frac{1}{r^2}\frac{\partial^2 p_{red,*}}{\partial \phi^2} - \frac{1-\omega_*^2}{\omega_*^2}\frac{\partial^2 p_{red,*}}{\partial z^2} = 0. \tag{24}$$

When we substitute for $p_{red,*}$ the earlier proposed solution in equation (20), we get:

$$\sum_{n,m}(\frac{\partial^2 P}{\partial r^2}+\frac{1}{r}\frac{\partial P}{\partial r}-(\frac{m^2}{r^2}-\frac{(n\pi)^2(1-\omega_*^2)}{\omega_*^2})P)e^{i(m\phi-\omega t)}cos(n\pi z)=0 \quad (25)$$

Since the last two terms will not become zero for arbitrary $r$, $\phi$, $z$ and $t$, we will need to solve:

$$\frac{\partial^2 P}{\partial r^2}+\frac{1}{r}\frac{\partial P}{\partial r}-(\frac{m^2}{r^2}-\frac{(n\pi)^2(1-\omega_*^2)}{\omega_*^2})P=0. \quad (26)$$

This is easily rewritten as:

$$r^2\frac{\partial^2 P}{\partial r^2}+r\frac{\partial P}{\partial r}+(\frac{(n\pi)^2(1-\omega_*^2)}{\omega_*^2}r^2-m^2)P=0. \quad (27)$$

If $\omega_* \leq 1$ the solutions of this equation are well known and given by:

$$P(r)=C_1J_m(ar)+C_2Y_m(ar), \quad (28)$$

where $a=\frac{n\pi\sqrt{1-\omega_*^2}}{\omega_*}$. Here $J_m$ denotes the mth order Bessel function of the first kind and $Y_m$ the mth order Bessel function of the second kind. Both functions go to zero for $r->\infty$ and the only singularity is that of $Y_m$ in $r=0$, where we don't need to solve our equations. Therefore both functions can be involved in our solution.

Now we will concentrate on finding an expression for $\omega_*$ that satisfies our boundary conditions. To start off, there will be no flow of water through the mantle of our cylinder, so that $u_r(R)=0$. From equations (16) and (17) we can find the following expression for $u_r$:

$$u_r=\frac{i\omega_*}{1-\omega_*^2}\frac{\partial p_{red,*}}{\partial r}-\frac{1}{r(1-\omega_*^2)}\frac{\partial p_{red,*}}{\partial\phi}. \quad (29)$$

Substituting equation (20) gives:

$$u_r=\sum_{n,m}\frac{i}{1-\omega_*^2}(\omega_*\frac{\partial P}{\partial r}-\frac{m}{r}P)e^{i(m\phi-\omega t)}cos(n\pi z). \quad (30)$$

For our boundary condition this breaks down to:

$$\omega_*\frac{\partial P}{\partial r}|_{r=R}-\frac{m}{R}P|_{r=R}=0. \quad (31)$$

Substituting equation (28) gives:

$$C_1(\frac{\partial J_m(ar)}{\partial r}|_{r=R}-\frac{m}{\omega_* R}J_m(aR))+C_2(\frac{\partial Y_m(ar)}{\partial r}|_{r=R}-\frac{m}{\omega_* R}Y_m(aR))=0. \quad (32)$$

It can be derived that:

$$\frac{\partial J_m(ar)}{\partial r} = aJ_{m-1}(ar) - \frac{mJ_m(ar)}{r}. \tag{33}$$

This also goes for $Y_m$, so that equation (32) can be rewritten as:

$$C_1(aJ_{m-1}(aR)-(1-\frac{1}{\omega_*})\frac{m}{R}J_m(aR))+C_2(aY_{m-1}(aR)-(1-\frac{1}{\omega_*})\frac{m}{R}Y_m(aR)) = 0. \tag{34}$$

Since we know that the Hankel functions display the type of spiral behaviour we are looking for, we rewrite equation (28) to the form

$$P(r) = D_1 H_m^{(1)}(ar) + D_2 H_m^{(2)}(ar), \tag{35}$$

with $C_1 = D_1 + D_2$ and $C_2 = i(D_1 - D_2)$ and with the Hankel functions defined as

$$H_m^{(1)}(ar) = J_m(aR) + iY_m(aR) \tag{36}$$

$$H_m^{(2)}(ar) = J_m(aR) - iY_m(aR). \tag{37}$$

However, since the ship is considered to be the source of the waves, $H_m^{(2)}$, which represents an inward moving spiral, would be an unphysical solution in this situation and we set $D_2 = 0$. The total amplitude for our solutions is arbitrary and so we can set $D_1 = 1$. Equation (28) then becomes:

$$P(r) = J_m(ar) + iY_m(ar) = H_m^{(1)}(ar), \tag{38}$$

Now we will try to use equation (34) to find the $\omega_*$ for which the boundary condition is met:

$$aH_m^{(1)}(aR) - (1 - \frac{1}{\omega_*})\frac{m}{R}(H_{m-1}^{(1)}(aR)) = 0. \tag{39}$$

We will first look at the solution when $m >> 1$ and $ar > m$. Under these assumptions $H_m^{(1)}$ goes with $\sqrt{\frac{2}{\pi z}}e^{i(z-\frac{1}{2}m\pi-\frac{1}{4}\pi)}$ and equation (39) can be rewritten as:

$$a\sqrt{\frac{2}{\pi aR}}e^{i(aR-\frac{1}{2}m\pi-\frac{1}{4}\pi)} - (1 - \frac{1}{\omega_*})\frac{m}{R}(\sqrt{\frac{2}{\pi aR}}e^{i(aR-\frac{1}{2}m\pi-\frac{1}{4}\pi)})e^{\frac{1}{2}\pi i} = 0, \tag{40}$$

which breaks down to:

$$a - (1 - \frac{1}{\omega_*})\frac{m}{R}i = 0. \tag{41}$$

Since $r$, $\omega$ and $a$ are real, the real part of this equation gives us the trivial solution $\omega = 1$. The approximation made above is not necessarily true and it is

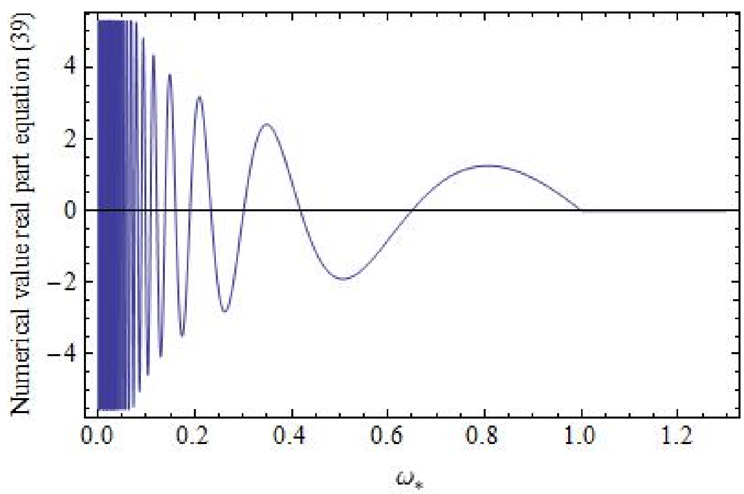


Figure 12: The results of plotting the real part of equation (39), for the fixed values R = 1, m = 1, n = 1

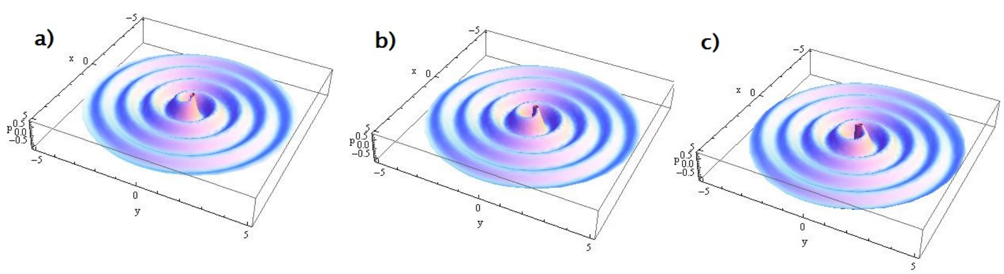


Figure 13: A plot of equation (42) for $\omega = 0.5$, $m = 1$ and $n = 1$: a) At $t = 0$, b) at $t = 0.5\pi$ and c) at $t = \pi$.

therefore also useful to study equation (39) without it. Of the real part of this equation a plot for fixed values of everything but $\omega$ is displayed in figure 12, to increase the understanding of the function we are trying to solve. It is clear that for $0 \leq \omega_* \leq 1$ there are indeed solutions to this equation. Therefore, we have found a solution to our problem of the form

$$p_{red} = \sum_{n,m} H_m^{(1)}(ar)e^{i(m\phi - \omega t)}cos(2n\pi z), \tag{42}$$

for certain values of $\omega_*$.

This equation can be numerically solved for $\omega_*$, when providing values for all other parameters. We can now look at the behaviour of the solutions. In figure 13 equation (42) is plotted for varying values of $t$, with all other parameters fixed. These plots include the solution inside the range of the cylinder representing the

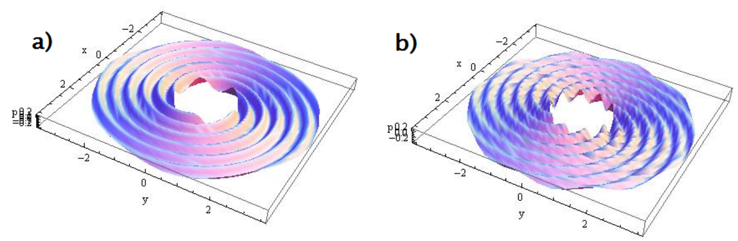


Figure 14: A plot of equation (42) with $\omega_*$ chosen as one of the solutions to equation (39) and $n = 1$ and $t = 0$: a) For $m = 5$ and b) for $m = 10$.

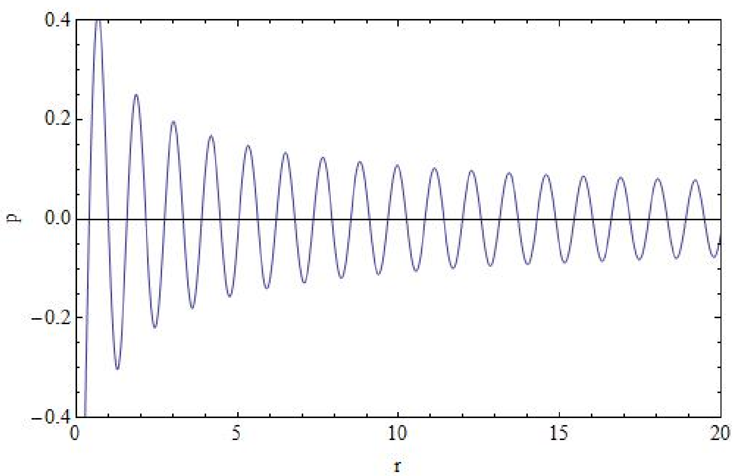


Figure 15: A plot of equation (42) for $\omega = 0.5$, $n = 1$, $t = 0$ and $m = 1$.

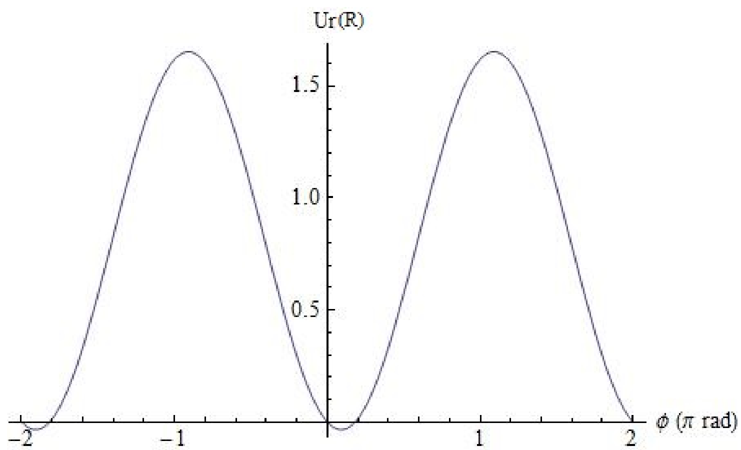


Figure 16: A plot of $U_r$ at $r = R$ for varying values of $\phi$, with $R = 1$, $n = 1$, $m = 1$ and $\omega_*$ is chosen as one of the solutions to equation (39)

ship to make the rotational behaviour visible. Though not clear from this figure alone, which is simply a spiral, the spoked behaviour we expect becomes visible for higher m, as shown in figure 14. These solutions have only been plotted outside the range of the cylinder. Clearly $m$ determines the number of spokes that the solution displays. As mentioned earlier, the solutions have singularities around the origin, and these singularities reach out to higher $r$ if we increase $m$, so for high $m$ these singularities could perhaps lie outside the bounds of the ship, which is one of the limitations of this simple approximation. Figure 15 shows that the amplitude of the spokes decreases for higher r, which is behaviour we would expect, seeing as how the lightwheels stop at a certain distance from the ship. However, figure 16 shows that though we have found an $\omega_*$ that satisfies the boundary condition for a certain $\phi$, namely for $\phi = 2k\pi$, with k an integer, the boundary condition does not hold for arbitrary $\phi$. This means that even though we have found a solution that displays the expected behaviour, this is not a correct solution to our problem.

Because this approach has provided no correct solution to our problem, we can also look at the case that $\omega \geq 1$. If that is the case equation 27 can be rewritten as:

$$r^2 \frac{\partial^2 P}{\partial r^2} + r \frac{\partial P}{\partial r} - \left(\frac{(n\pi)^2(\omega_*^2 - 1)}{\omega_*^2} r^2 - m^2\right) P = 0. \tag{43}$$

This differential equation has the modified Bessel functions I and K as its solutions. Since I is an exponentially increasing function and K an exponentially decreasing function, we discard I in this scenario. We can follow our previous analysis, only now with $b$ instead of $a$, where $b = \frac{n\pi\sqrt{\omega_*^2-1}}{\omega_*}$ and $K_m(br)$ instead of $H_m(ar)$. Unfortunately if we try to find a solution for $u_r = 0$, the equation that follows has no solution for $\omega \geq 1$ and so this approach is also ineffective.

This means that even though we tried to find solutions here that give an indication of what a magnetic field in the real situation could do, we should be careful when we draw conclusions. For example, we have worked with a uniform B-field while if we really expect that the ship's magnetic field is the cause of the waves, an entirely different solution could be found. The B-field used here is orthogonal to the sea surface, so it isn't representative for the Earth's magnetic field either, which is parallel to the sea surface. Additionally, we have only solved the linearised equations, not to mention that we have approximated the ship with a cylinder. This means that the real problem is a lot more complicated than our approximation and even a more thorough and correct analysis of the problem portrayed here can only take us so far. Then there is the issue that we have not been able to satisfy one of our boundary conditions, because even in our best approximation to a solution there is net flow of water through the wall of the cylinder. Sadly, due to time constraints a more satisfactory solution has not been found and the figures shown here are the closest we have gotten to a solution.

However, what we have shown is that when we solve the equations for this magnetic field, that the corresponding solutions possibly display some of the behaviour we would expect. The form of equation (42) tells us that there is an oscillation dependent on $\phi$, which will mean that a pattern of spokes emerges (figure 14), which due to the dependence on $r$ will decrease for increasing $r$ (figure 15) and will rotate in time (figure 13). Additionally we have shown that in our situation it is possible that if Hankel functions are involved these spokes become curved, as has been shown in our figures, therefore creating the pattern we expect for the lightwheels. The rough symmetry of a ship along its length would probably cause a symmetrical flow pattern in the real situation too and additionally it is likely that when solved for the real situation the solutions will also include Hankel or other Bessel functions in some form or another, which means that a spoked pattern like that of the lightwheels can arise. Therefore, though our analysis does not provide definitive proof that the magnetic field of a ship creates the pattern of the earlier described lightwheels, it should provide incentive to further analyse this problem with more realistic and complete starting conditions and a more extensive analysis of the solutions that arise.

As a closing note for this chapter it is important to give a reminder that we have only solved the problem for negative ions. This means that even though the positive ions will move under this B-field too, they will do so in the opposite direction. If we also take into account that the water molecules resist the flow of ions, it becomes clear that it is unlikely that any net flow of water will occur. The flow of ions could trigger bioluminescence if the B-field is sufficiently strong, due to the tension arising from the moving ions, but this should not be mistaken with a general flow of the water. This is also why the Earth's magnetic field will never have influence on the flow of ocean water on large scales, since the ocean water as a whole is neutrally charged.

## 4.4 Auroras

Because in several reports the similarity between the appearance of the lights in the Arabian Sea and the auroras in the Arctic and Antarctic regions has been noted, it can prove useful to study the mechanics behind an aurora and see if anything similar is possible in the regions we are interested in. Aurora is the name for a collection of phenomena appearing mainly around the Arctic and the Antarctic regions, where lights of varying colors and brightness appear in the sky, both above the observer, as well as further away on the observer's horizon. Auroras are generally associated with the solar wind, which consists of positive and negative ions emitted by the Sun. These ions are then directed and accelerated toward the North and South Pole due to the Earth's magnetic field. During this process a collision with both oxygen and nitrogen atoms will cause these atoms to become excited. When they return to their normal states on time scales varying from milliseconds to minutes (the oxygen green state), they will emit a photon of a specific wavelength, so that uniform light is created. (Chamberlain, 1995)

Due to the deflecting nature of the Earth's magnetic field only part of the solar wind ever reaches the Earth's surface and most of that part is directed toward the Polar Regions. This is why only during extreme increases of the solar wind's intensity, auroras have appeared at somewhat lower latitudes. Furthermore, due to the increased air density on the Earth's surface in comparison to its higher atmosphere, any ion that penetrates the Earth's magnetosphere is very likely to collide long before it reaches water level. It is therefore unlikely that the solar wind can reach the Earth's surface on latitudes as low as 10N, the latitude we are interested in. However, it does prove an interesting perspective on the problem, since the cause could lie in eccentricities of the Earth's magnetic field around the Arabian Sea.

## 4.5 Ball lightning

For the same reasons that we have looked at auroras, we can also look at the phenomenon called ball lightning. The reason it is brought up here is that, at a first glance, it shows some similarities with the earlier mentioned light balls and therefore it is worth to look at the different theories behind ball lightning, if only to provide some inspiration. Like the phenomena we have looked at, ball lightning has not been completely explained by modern science either. Ball lightning has been around for much longer than any lights discussed here and has also not been geographically limited in any way (Corliss, 1977; Hentschel, 1993). It is observed in many forms, but the general description of the phenomenon is that of a ball of light with a typical diameter of half a meter. In most of the reports it appeared to hover near the observer and it ends up exploding, in some cases damaging the surroundings. If the ball was touched it was reported to be hot and it has been known to leave red spots on the body and sears of the clothing. All this strongly indicates that it is not related to the balls of light we observed, since any heat source in water would simply be extinguished and the balls can therefore not exist in water for very long. Most of the observed ball lightning also takes place during lightning storms (Smirnov, 1987), while in our case most reports indicate calm and clear weather conditions. Moreover the reports generally describe the balls as hanging still or slowly moving, nothing like the light balls shooting up from the ocean. It is therefore highly unlikely there is any connection between the two and there will therefore be no further elaboration on any of the theories behind the ball lightning.

# 5 Experiment

## 5.1 Introduction

Some of the questions regarding the triggering of bioluminescence in dinoflagellates that have been offered cannot completely be answered with theoretical research. Therefore an experimental approach has also been attempted to solve some of these remaining questions, especially those that have not been studied by any other experiments. Though the experiments sadly had to be done under strong time constraints due to an oncoming deadline, it did provide a great opportunity to put some of the theories to the test. The first part of the experiment will be to see what effect a constantly moving object, resembling a ship, has on the dinoflagellates. This effect should not be too strong, because none of the reports indicate strong triggering of light aside from the light wheels. However, it is expected that some bioluminescence is triggered, because the ship causes a disturbance of the flow surrounding the dinoflagellates. Secondly, we will look at the effect pressure waves have on the algae, because pressure thresholds have only been determined for complete pressure changes in the water, which is not what we are interested in. Hopefully, localized bioluminescence can be triggered and if that is the case it may enable us to study what happens at the ocean surface. Lastly, we will try to create some bioluminescence with magnetic fields, be it through a changing magnetic field on the water, or through the combination of a magnetic field and a metal object moving through the water. Due to the relative simplicity of our experiment, it is highly unlikely that we will reach anything close to the pattern we are looking for, but we do hope to find some additional bioluminescence if a magnetic field is applied.

## 5.2 Methods

The algae used in the experiment were Noctiluca Scintillans. Noctiluca Scintillans, also known as Sea Sparkle, are a relatively large species of dinoflagellates, ranging from 200 to 2.000 $\mu$m and are responsible for most of the bioluminescent displays around the Netherlands, but are also found in the Indian Ocean. For the experiments we used 30 litres of seawater with a high concentration of the algae, taken from the Wadden Sea. This concentration was reached by filtering the seawater with a 50 $\mu$m filter and flushing the filtrate out with fresh seawater. The algae were therefore kept in the same seawater in which they are normally

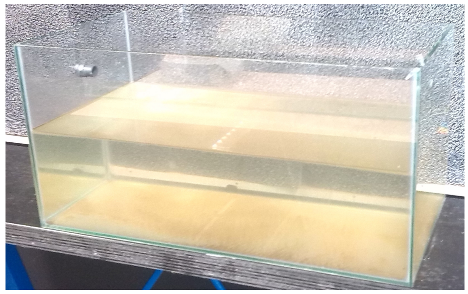

Figure 17: The tank with Noctilluca Scintillans.

found, only in a higher concentration. They were kept in a tank, displayed in figure 17, in a 15 °C climate room, subjected to a 16:8 light:dark cycle. Before each experiment the tank was obscured from light for at least 2 hours, to bring the dinoflagellates to rest. After this period the tank was placed in a dark room where all experiments took place. To look at the effect of ships on algae a small plastic boat was pulled through the water. To create pressure waves a speaker was connected to a pulse generator with an amplifier in between. For inducing a magnetic field two magnets of up to 1 MT were available. For the part of the experiment where magnets were involved, the table was placed on a wooden table to minimize side effects of any nearby metal. Attempts were made to capture the observations on camera, but none of these provided useful images, as will be discussed later. Therefore the results have only verbally been recorded.

## 5.3 Results

The first part of the experiment revolved around finding out how strong the bioluminescence of the algae in reaction to direct stimulation by movement of water was. We found that even when the tank was left untouched some algae still emitted light, reminiscent of a starry sky. This happened only on the surface of the water, which makes it likely that it was no spontaneous emission, since that would take place throughout the fluid, but rather stimulation by some very weak surface waves. When the model ship was pulled through the fluid, only the water in direct contact with the ship lit up and relatively weakly so. Of course since in our experiment we scaled down everything but the threshold of the dinoflagellates it may well be possible that the larger forces involved with a larger ship do trigger strong bioluminescence. On the other hand, on a real ship one would look at the bioluminescence from farther away, so that this increase in light may be compensated by the increase in looking distance. Additionally, even quick movement and acceleration of the ship did not trigger any more bioluminescence in the bulk of the fluid. The waves caused by the ship were only visible at the edges of the fluid, where they collided with the walls of tank. The most likely explanation is that ships are made to cut through the water, rather than push through and this cutting movement causes a lot less instant displacement of water, which is what the algae respond to. The relatively slow displacement by bow waves may not be enough to trigger bioluminescence. It was possible to strongly stimulate the algae by giving a hard tap to the side of the tank, leading to a quickly dissipating wave of light moving from the sides of the tank towards the middle of the tank.

The simulation of the P-waves triggered little bioluminescence in the fluid. The only bioluminescent response was triggered at the instant that the speaker was turned on, though even that response was weak. That response could very well be due to physical stimulation when the membrane of the speaker starts to move instead of any shockwave effect. That no other response was triggered could of course be because the theory is flawed, but it could also be because of a few problems with the set-up. Since the speaker available was quite a basic one, the signal that was emitted could not be amplified very much without blowing up the speaker and was therefore quite weak. Additionally, the lower limit for the frequency that could be emitted was around 60 Hz, whereas P-waves have a typical frequency of around 1-20 Hz. We did want to get as close to that frequency as possible and therefore did our experiment with a signal of 40-60 Hz. The consequence of this choice was that the emitted signal was barely audible. Since the sound pressure of a normal conversation lies around 0.02 Pa, we can safely assume that the signal we emitted had a pressure below this level. We do not know the exact pressure at which bioluminescence is triggered, but $2 \cdot 10^{-5}\%$ of ambient pressure does seem a very weak perturbation. It is therefore possible that stronger perturbations, maybe also at lower frequencies, would trigger the expected response, which means that the experiment provides no conclusive evidence with respect to pressure waves.

When we applied a magnetic field to the tank, neither of the two magnets seemed to trigger any response. To look at the effect a ship would have in such a uniform magnetic field, representative of the Earth's magnetic field, we pulled a metal object through the fluid. The triggering of bioluminescence when the magnetic field was applied, was no different from when it wasn't applied. Because the tank we used didn't allow for long movements of the metal object, it was a bit hard to compare the two situations, but due to the strength of the magnets we used compared to the weak field of a ship, the response resulting from this should have been strong enough to notice. Therefore our experiment seems to indicate that no magnetic field will create bioluminescence in the scenario that we created. It could of course be that we used an incorrect set-up to find a bioluminescent reaction and when taking into account the conditions under which the experiment was done, the possibility of stimulation by a magnetic field can not yet be excluded. However, it does offer the question what we did wrong in the experiment, which is one that should be answered before any further experiments are attempted.

An interesting side-effect we were able to study during the experiment was the exhaustion of the algae. Literature suggested that after having emitted light for a while, the algae would no longer emit any light, without giving an indication of the time span on which this occurred. Though we put no explicit research into this aspect, we did notice that the exhaustion of dinoflagellates was only apparent for approximately 3-5 seconds after stimulation, after which they were able to emit light again. Permanent exhaustion was only detected when repeatedly stimulating the algae for over 90 minutes and even then the only effect was a slight diminishing of the emitted light. Given the far from ideal circumstances of our experiment, it is unlikely that on the timescale the phenomena take place, any of this permanent exhaustion would be of influence. This means that if the algae are indeed responsible for the observed phenomena, the only exhaustion would be a diminishing of the amount of light that is emitted for a few seconds. This could be something observers should have noticed, but we should also consider that in the ocean the amount of water available is many times the amount we used. Therefore a relatively small flow of water can introduce a large amount of fresh algae into the wheel, so that none of this exhaustion would be visible.

As mentioned, we have made several attempts to capture the bioluminescence on camera. To do this a highly sensitive camera that could measure up to 16.000 iso was used and several shots of, what was to our eyes very bright, bioluminescence were taken. Unfortunately, these pictures gave a signal on the same order of magnitude as the noise that was picked up and lower iso settings gave no signal at all. This does mean that some signal was recorded, since pictures taken of the tank gave significantly higher pixel values than those taken with the lens cap on. However, the weakness of the signal didn't allow us to record patterns in the bioluminescence in the way we had hoped. In the end this is not surprising, since most cameras indicate that the useful range for recording in which noise isn't too dominant, lies below 3200 iso. The other attempts were even less fruitful, since a less sensitive camera picked up no signal at all and a camera with night vision only showed us the tank and the water, but not the lights.

What these endeavours do indicate, is that the light emitted through this bioluminescence was extremely weak. Because the eye works on a logarithmic scale, it enables us to pick up these weak signals if we give it the time it needs to adjust to the dark environment and even these weak lights can appear to be bright. Since cameras work on a linear scale, they have far more difficulty with picking up these very weak signals. Most other experiments involving bioluminescent algae used photomultipliers or image intensifiers to enhance the signal, but unfortunately these were not available to us. This does shed some light on the issue that no photographic evidence of the phenomena exists. Due to the amount of the observations it is probable that at least a few of the ships had a camera on board and one would expect that when something like a lightwheel is observed, this camera would be used to record it. However now that we know how weak the light emission can be, this peculiarity is far easier to understand, since it is improbable that a device such as a photomultiplier would be taken on board. The lights could seem bright to the observer, because his eyes would be adjusted to the dark, while in fact the lights can be so weak that a camera wouldn't pick them up.

It should be mentioned that the circumstances under which the experiments were done, were far from ideal. All experiments took place in a dark room, but the climate in this dark room could not be controlled. As a consequence the algae were sometimes placed in this relatively warm room for over two hours, which would have warmed the water up quite a bit. During our experiments we also strongly disrupted the diurnal cycle of the dinoflagellates, because we could not control the light/dark rhythm of the climate room. This means that after just a few hours of light we would place the dinoflagellates in the dark again for two hours, after which the experiments began. Additionally, we moved the algae to the dark room only just before the experiments to minimize their time in this relatively warm room, but this probably lead to quite a lot of triggering of bioluminescence on the turbulent trip to the dark room, which means that bioluminescent exhaustion could have taken place before the experiments even begun. All these restrictions mean that all the results we found should be considered as lower limits: If no bioluminescent response took place, this could also be because of these far from ideal circumstances. This is especially true for the results we found for the exhaustion time of the algae, which when measured under perfect circumstances would probably be significantly longer. In addition to these restrictive conditions, we have also studied but one type of dinoflagellates, whereas strong indication exists that different types of algae exhibit different behaviour. However, because no evidence was ever found that different types of dinoflagellates could be triggered by completely different mechanisms, the qualitative nature of our experiments suggests that most of our conclusions hold for other dinoflagellates as well.

# 6 Conclusion

In this thesis the varying theories that have been put forward to explain the phenomena known as marine lightwheels and light balls have been analysed and discussed. It has become clear that even though most theories do provide a decent explanation for the phenomena at first sight, a closer look shows that they all fall short in explaining some aspects of the observations. This either means that the final theory concerning the phenomena has not yet been found, or that different versions of the phenomena also need different theories. This last option may seem like a stretch, because the different phenomena all seem to take place in the same area and in the same time frame, which would indicate that the different theories that have been discussed should all have the same very specific requirements. However, using the same explanation for all of the different observations is also unsatisfying, because of the great variation between them. For example, the different lightwheels may all seem like the same phenomenon because of their great resemblance to each other, but is a lightwheel that is centred and fixed on an arbitrary point really the same as one centred on and moving along with a ship? Because the first one indicates that the ship is merely an observer, whereas the second version indicates the ship takes part in the creation of the wheel.

So we have the specific circumstances under which the phenomena have taken place and the similarities between the phenomena, which both indicate that a single theory should be found. On the other hand the variations between the different phenomena show us that multiple theories with the same specific requirements should be found. For now this second option has been shown to be more promising through the different theories that quite accurately explain specific aspects of the phenomena. The seismic explanation shows great promise in explaining the light balls through seismic P-waves that can possibly trigger bioluminescence. The magnetic field of a ship in conjunction with bioluminescence seems to be capable of creating some sort of spiral pattern which could turn out to be a wheel with curved spokes centred on a ship. This theory is still in its infancy, so further analysis, be it numerical, analytical or experimental, could provide us with more answers and is therefore greatly encouraged. Also it has turned out that the grand displays of the lightwheels with their center points on the horizon are possibly a different phenomenon than the ones with discernible center points, namely parallel beams that only seem like a lightwheel due to optical illusion.

These theories do leave a few questions unanswered. Firstly, the origin of the lightwheels neither centred on the horizon, nor on the ship, remains unknown. They could be created by seismic waves, though the required circular form of these waves and the fact that you need two point sources close together do indicate that this theory is probably not the correct one in its current form. They could also originate from the trapping of the waves around a seamount which in roughly the same way as in our magnetic theory could lead to spiralling behaviour when waves are formed by for example the Coriolis force (LeBlond and Mysak, 1981). This provides an additional advantage, because this trapping is stronger for relatively high seamounts compared to the ocean depth, so that in practice the phenomenon is more likely to take place in shallow water, which we have found to be the case. Sadly, this theory only came to light at the end of the research period, so that it has not been explored more thoroughly. The source of the parallel lightbeams also remains unknown. They could be caused by seismic waves, but analogous to using them for the lightwheels, there are a lot of requirements to this theory that are unlikely to be met. The more likely explanation would be that they are caused by the lensing by surface waves of light emitted by for example bioluminescence. However, this does offer the question why light would be uniformly emitted over such a large area and how the surface of the ocean could be rippled so consistently over a large area.

Our experiments provided an opportunity to gain some more practical insight into the behaviour of the dinoflagellates. However, it is dangerous to draw any conclusions from the experiments, because of the flawed conditions under which they had to be done. Even when taking into consideration the circumstances, they do seem to indicate that the magnetic fields induced by ships are unable to trigger bioluminescence. This could be because the set-up of our experiment didn't resemble the real situation closely enough, so a magnetic theory can't yet be excluded, but it does raise some doubts regarding this theory. On a positive note, they also indicate that in the time the phenomena take place, no exhaustion of the dinoflagellates would occur. The experiments also showed us that, though bright to the eye, the emitted light is so weak that it is nearly impossible to obtain photographic evidence of the phenomenon. No conclusive evidence is found regarding pressure waves, but the movement of the ship in the ocean should trigger bioluminescence closely around the ship.

As of yet it remains unclear where some of the specific circumstances that are seemingly required for the phenomena come from. Ideally they should come from the dinoflagellates, since they are a common denominator among the different theories. We have shown that the circadian rhythm of the dinoflagellates can explain why the observations are only done in the night. The location of the phenomena around the Arabian Sea could be due to a specific strain of dinoflagellates that only lives there, but this is unlikely, because there is no clear reason why they would have developed different thresholds in the Arabian Sea than anywhere else. Also, the combination of seismic activity with bioluminescent dinoflagellates would narrow down the area in which the phenomena could occur, but the combination is not exclusive to the Arabian Sea and is not required for every theory. The specific timeframe in which most observations have been done could have several reasons. The development of iron ships and the wide implementation of them could have been key in initiating the events. The reduction of observations over the past 40 years could have been due to pollution of the ocean, which reduces the amount and productivity of dinoflagellates, or due to the magnetic masking, or degaussing of the iron ships. That all but one of the observations have been done from motorised, iron ships could be explained by the magnetic field theory. Though only very briefly discussed in this paper the frequency of the wheels suggests the waves caused by the motor of a ship also have an important part in the making of the lightwheels. It could of course be a coincidence, but for the sake of completion it has to be noted. As has become clear now most of the circumstances can be partially explained, or at least some indication as to why they are there can be given. It is hard to fulfil them all at the same time, mainly because of our decision to look at separate theories, but presented here is a closer approach than most of the other research was able to make.

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