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THE NORTHERN LIGHTS PHONOMENON
Detect and predict them

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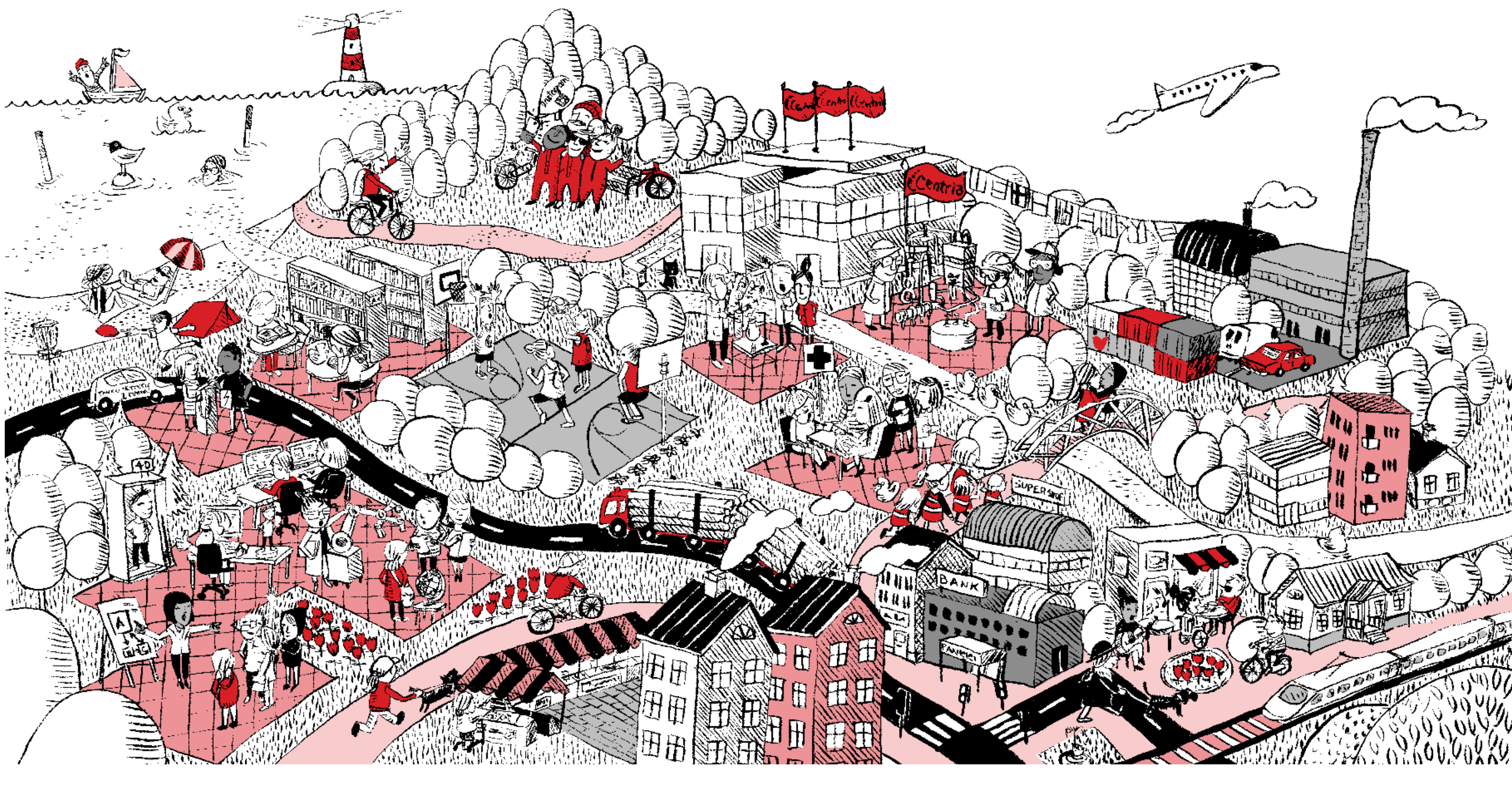

ABSTRACT

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For a long time considered as supernatural phenomena, the polar auroras have fascinated mankind, and still do today. Over the centuries, scientists have tried to prove that these phenomena had nothing divine but everything physical. It was not until the 18th century that Birkeland realized a device to recreate auroras. Today, scientific institutions such as the National Aeronautics and Space Administration and the European Space Agency are constantly observing and analysing solar activity, which is responsible for meteorological changes, but also for the appearance of polar auroras.

This thesis is composed of seven main chapters in which it is explained how the northern lights are formed, from their origins to their appearance in the sky. There are also the myths and legends around which the aurora has been talked about, as well as the way to detect and predict them.

It is possible to note that the aurora borealis involves various physical and chemical phenomena, of a complexity both at the atomic level and at the macroscopic scale. The detection of the aurora borealis includes several criteria such as the Kp index, the presence of clouds and light pollution. As for their prediction, despite today's new technologies, accurately predicting the arrival of this phenomenon remains a very complicated task that requires time.

Key words
Northern lights, aurora borealis, astronomy, Sun, Earth, solar wind

CONCEPT DEFINITIONS

CME: Coronal Mass Ejection

DSCOVR: Deep Space Climate Observatory

DSN: Deep Space Network

ESA: European Space Agency

GPS: Global Positioning System

NASA: National Aeronautics and Space Administration

NOAA: National Oceanic and Atmospheric Administration

SOHO: Solar and Heliospheric Observatory

ABSTRACT
CONCEPT DEFINITIONS
CONTENTS

PICTURES

FIGURES

1 INTRODUCTION

Like rainbows, lightning or earthquakes, the northern and southern lights are part of the natural phenomena that have long provoked fear and curiosity in humans. Considered for centuries as supreme celestial beings, bridges to the beyond, or as dangerous watches, signs of bad omens, these long colored draperies (PICTURE 1) still occupy today an important place in the myths and ancient legends that everybody enjoy hearing around a campfire. But behind these stories there is a very scientific explanation, which philosophers and astrophysicists around the world have tried to explain. Current technologies and recent discoveries of the 21st century have allowed us to better understand this phenomenon. But what is hidden behind this luminous phenomenon that are the auroras? How to detect and predict them? This is the subject of this thesis.

PICTURE 1. Aurora borealis photographed in Alaska, February 2000 by Dick Hutchinson (Teste 2013)

This thesis is divided into 7 chapters, including the introduction and conclusion. After having exposed the historical context through myths and legends coming from various horizons, the second chapter will deal with the fundamental scientific advances which allowed the understanding of the aurora today. In a third and fourth chapter, it will be possible to see and understand the formation of the aurora from the Sun and the Earth to their colored appearance in the sky. Finally, the last chapter will allow to discover if it is possible today to predict the appearance of polar auroras on Earth.

2 GENERAL INFORMATION ABOUT AURORA

The polar lights have been seen from many different angles through the ages, whether they are bad omens, divine signs, or just a visual effect explainable by science. Let's find out what is behind this phenomenon.

2.1 Definition of an aurora

The etymology offers the beginnings of an answer. The name comes from the Latin "aurora borealis". Aurora means sunrise, which is also the name of the Roman goddess of dawn. Borealis is a Greek reference to the north wind. (Bourgeois 2020.)

An aurora borealis, or northern lights, is a polar aurora visible in the northern hemisphere only. There are other polar lights visible this time in the southern hemisphere called the southern lights or aurora australis. Therefore, a polar aurora is defined as an atmospheric luminous phenomenon, essentially visible at the highest latitudes of the Earth, when electrified particles are precipitated in the upper atmosphere (FIGURE 1). The polar aurora can be seen in areas closest to the "auroral zone," an annular zone that lies between 65- and 75-degrees latitude. (Futura Sciences 2021.)

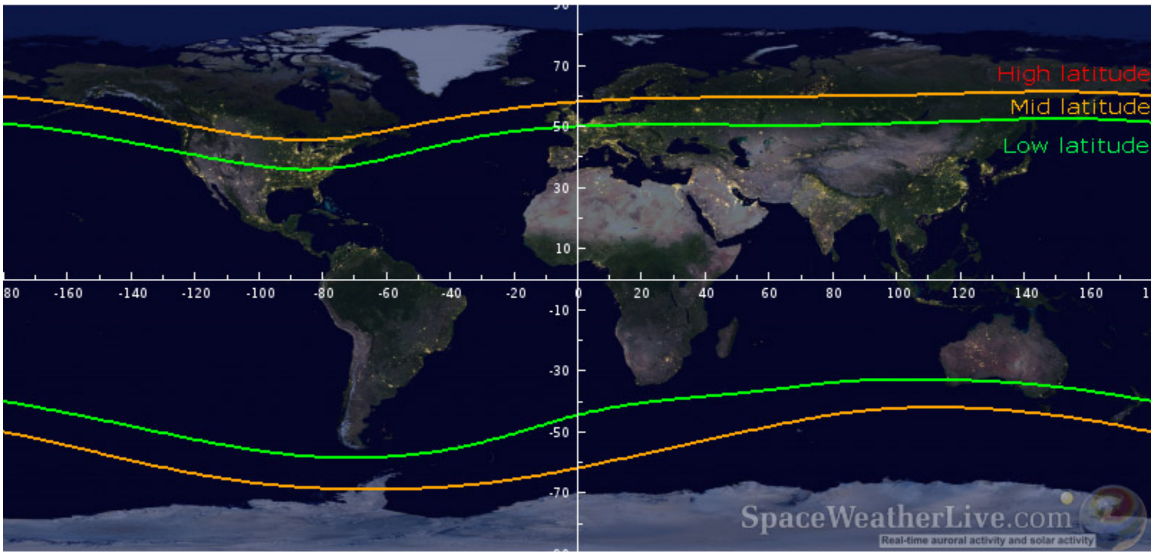


FIGURE 1. World map representing the different latitudes (SpaceWeatherLive)

In the northern hemisphere, the Scandinavian countries have a front row seat. In Norway, for example, the city of Tromsø has an annual outdoor festival in honour of the Northern lights, and in 1899 the city of Alta acquired the first observatory. In Finland, the place where it is the most likely to see the Northern Lights is in the far north of Finnish Lapland, in the region of Kittilä, a town located 170 km above the Arctic Circle, or to the towns of Inari and Kaamanen. In Iceland, it is necessary to move up to the small village of Kálfafell or the very isolated village of Sandgerdi to have the chance to see the aurora. In Danish territory, this is the Faroe Islands. In a very good place, the island of Greenland and the city of Kangerlussuaq offer a spectacle in a most supernatural setting with its glaciers and these arctic landscapes. In northern Canada, Alaska is distinguished by one of the lowest pollution rates. Jasper National Park, located in the Rocky Mountain Nature Reserve, offers good sky visibility. The cities of Fairbanks and Yellowknife are great places to see the Northern lights. (Futura Sciences 2021.)

In the southern hemisphere, the land being further from the pole, the polar auroras are less intense and lower. The Antarctic plateau is occupied only by rare research stations, among others the Franco-Italian station Concordia. Therefore, the notion of "Northern lights" will be mainly used in the remainder of this thesis. However, it is possible to observe these southern lights, not very intense, in Patagonia, between Argentina (starting point in Ushuaia) and Chile (in Punta Arenas), as well as in Oceania, south of New-Zeeland and on the island of Tasmania. (Futura Sciences 2021.)

The best season to see an aurora is the polar night period: from September to March in the northern hemisphere, and vice versa in the southern hemisphere, from March to September, between 6 p.m. and 1 a.m. However, as close as possible to the magnetic poles, there is ultimately no ideal season since in the annular zone, there are some 200 nights per year of psychedelic celestial outbursts. (Futura Sciences 2021.)

2.2 Myths and legends

For centuries, northern civilizations have been fascinated by the Northern Lights. Without scientific explanation, their amazement and fear turned into myths and legends as these peoples sought to decipher the meaning of these light shows.

2.2.1 Scandinavian myths and legends

During the time of the Vikings, in the Scandinavian countries of Europe and the North Atlantic, some legends said that the Northern Lights were the reflection of the armor of the Valkyries; wonderful warriors charged to lead the warriors who died in battle to Valhalla, home of the gods (Hurtigruten NK).

For the Sami, a Finno-Ugric people, the Northern Lights were a bad omen. Indeed, considering them as the souls of the dead, many Sami still think today that it is very dangerous to provoke the auroras by gesturing, whistling, or singing when they unfolded in the sky, because then they might notice your presence and take you to the sky. In Finland, a fabulous myth says that it would be the arctic foxes who produce the aurora. These fire foxes would run across the sky at such speed that the fur of their large tails, rubbing the surrounding mountains, set off sparks lighting up the night. (Icelandair 2018.)

2.2.2 Myths and legends of North America

Some Native American beliefs explain that the Northern Lights are like torches held by the spirits responsible for accompanying the dead to a land of light and abundance. To communicate with humans on Earth, the Native American people believed that the auroras emitted a sound like a whistling, to which they had to respond by whispering. The Eskimo tribes, on the other hand, believed they could invoke the aurora to converse with their deceased family members. (Hurtigruten NK.)

In Canada and northern Michigan, the Algonquin tribes believed the aurora was a reflection of the gigantic fire lit by Earth Creator Nanabozho, having travelled far north, and letting his people know that despite the distance, he kept thinking of them. For the Fox Indians in Wisconsin, the Northern Lights were the spirits of their vanquished enemies, roaming restlessly and seeking to return from among the dead to quench their thirst for vengeance. They were a harbinger of war and disease. Like in Alaska, where Inuit communities also feared these lights and carried knives to protect themselves from the evil spirits of the aurora. (Hurtigruten NK.)

2.2.3 European myths and legends

When the Northern Lights appear in the south, in Europe, they often take on a reddish hue, which often aroused the fear of Europeans and seen as a harbinger of war. This was particularly the case at the end of the 18th century, during the French Revolution. Weeks before the monarchy was overthrown, a bright red aurora was seen in England and Scotland, and witnesses said they heard immense armies clash in the skies. (Hurtigruten NK.)

But the Northern Lights were not seen by all as harbingers of misfortune. Many cultures in northern Europe saw them as a favourable sign. The Estonians, for example, believed that the aurora were magical sledges, bringing guests to an unparalleled wedding in Heaven. Swedish fishermen were delighted to see an aurora, because they saw the reflection of gigantic schools of herring nearby. For them, aurora was a sign of good fortune and the promise of good fishing. (Icelandair 2018.)

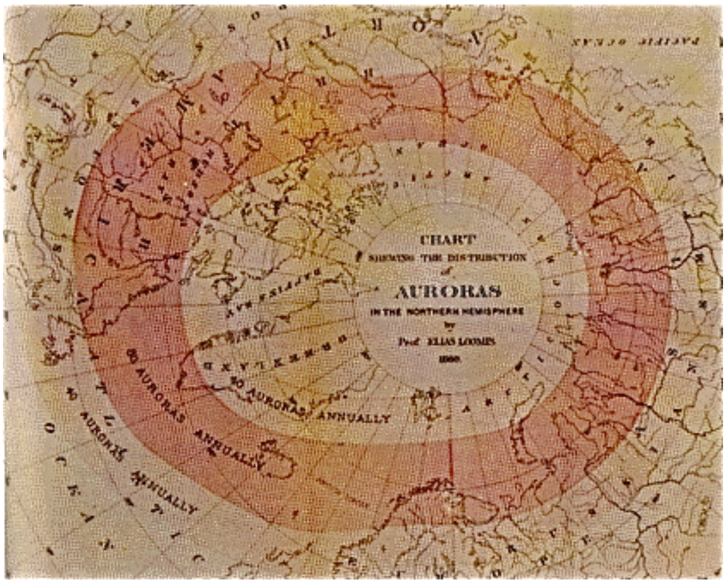
There are many other myths and legends about the Northern Lights, each older than the last. However, starting in the 19th century, scientists around the world began to hypothesize about the appearance of these light shows.

2.3 History

Historically, the first written description of the aurora dates to 2600 BC in Chinese annals. But the Northern Lights did not always carry this name, the first to have baptized them was Galileo, in 1620 (Gretry 2014). Scientists of the time began to take an interest in the phenomenon, but the theoretical shortcomings of physics made it difficult to approach it serenely. It was not until the progress of the 18th century, especially in optics and in the fields of magnetism and electricity, to begin to provide satisfactory elements of analysis. (Bernard 2018.)

2.3.1 Loomis map

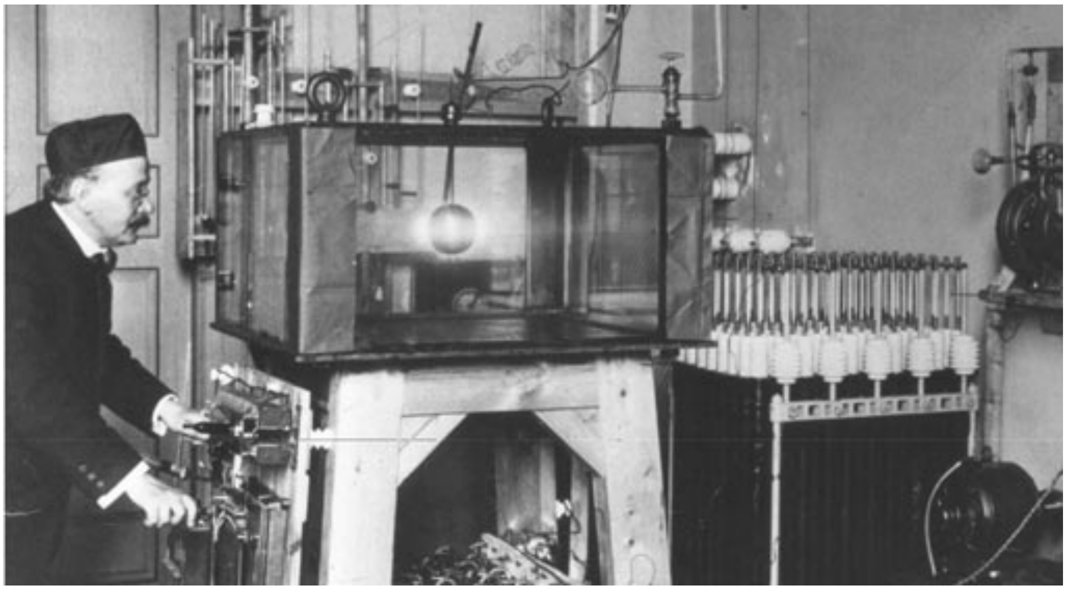
In 1860, Elias Loomis, an American meteorologist at Yale University published the first known map of the frequency of occurrence of the Northern Lights (PICTURE 2). It is possible to see on this map that the frequency of the auroras decreases as it approaches the magnetic north pole, to be almost zero at the level of the latter. Due to its shape, the band with the maximum frequency of the aurora (area in red on the PICTURE 2) was given the name auroral oval. His work was taken up by the German scientist Hermann Fritz, who then drew up a list of recorded northern lights in 1870, then a map in 1881. (Bernard 2018).



PICTURE 2. Aurora frequency map, Elias Loomis, 1860 (Bernard 2018)

2.3.2 Birekland's experiment

At the end of the 19th century, the Norwegian physicist Kristian Birkeland was the first to demonstrate the existence of the electron. He was also the first to hypothesize that the Northern Lights were created because of the emission of a stream of electrons from the Sun that would be trapped in the Earth's magnetosphere. To verify his theory, Birkeland reproduced an aurora borealis in the laboratory with an artificial iron earth magnetized by a right magnet, bombarded by cathode rays inside a vacuum chamber. All was connected to a high voltage generator making it possible to establish a potential difference of a few kilovolts between the cathode and the ball (PICTURE 3). The experience was a success. Knowing the maps of Loomis and Fritz, Birkeland explained the phenomenon of the Northern Lights and called his invention the *Terrella.* (Bernard 2018.)



PICTURE 3. Kistian Birkeland with his Terrella (Bernard 2018)

2.3.3 NASA THEMIS mission

Thanks to the scientific advances of the past centuries, on February 17, 2007, NASA (National Aeronautics and Space Administration) sent into space 5 satellites to measure and study the different energy discharges in the magnetosphere responsible for the polar auroras: This was the THEMIS mission (Time History of Events and Macroscale Interactions during Substorms). (Hatfield 2021.)

In July 2008, the data collected thanks to this mission made it possible to provide a coherent explanation of the phenomenon of the polar aurora. Scientists now understand how the constant outpouring of solar matter, called the solar wind, entangles the Earth's magnetic field, causing substorms. Finally, the THEMIS mission also made it possible to learn more about space weather and its forecasts to ensure the safety of astronauts and spacecraft operating around the Earth. (Hatfield 2021.)

3 AURORA’S MECHANISM

The aurora is a very complex physical phenomenon that involves various actors and several interactions. To understand how they are formed, it is necessary to explain the activity of the Sun, that of the Earth, and then the interaction that exists between the two. This is a phenomenon that humans were able to demonstrate only in 1958 thanks to the work of the American astronomer Eugene Parker. (Luxorion NK.)

3.1 Sun’s activity

The Sun presents on its surface permanently spots, flares, and faculae. This set of phenomena is called solar activity and can have many consequences such as the disruption of the climate on Earth. Solar activity can also be the source of solar storms that cause magnetic storms. These storms will disrupt communications or cause electrical system surges. In the past, more violent storms had already occurred, as in 1989, causing a total blackout in Quebec for nine hours. But magnetic storms can also cause the aurora borealis. (Milhat 2022.)

3.1.1 Solar wind

The Sun is the star of the solar system. It is composed (by number of atoms) of 92.1% hydrogen and 7.8% helium, but also contains 0.1% metals. The temperature on the surface of the Sun is 5800°C while in the center it reaches 15 million °C with a pressure of 2850 million atmospheres. The temperature and pressure there are so great that nuclear fusions take place in the heart of the Sun: hydrogen atoms (deuterium and tritium) collide and merge to create helium atoms, releasing a considerable amount of energy (blue balls are protons and white balls are neutrons on FIGURE 2). The energy released by the Sun is continuously ejected in all directions in the form of plasma (gas with ionized particles) called solar wind. The zone of influence of this wind is called the heliosphere and it extends to the confines of the solar system. (Christophe 2022.)

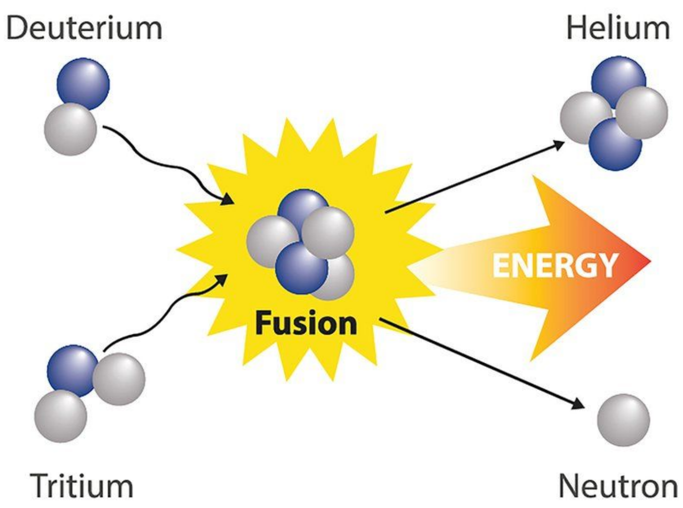
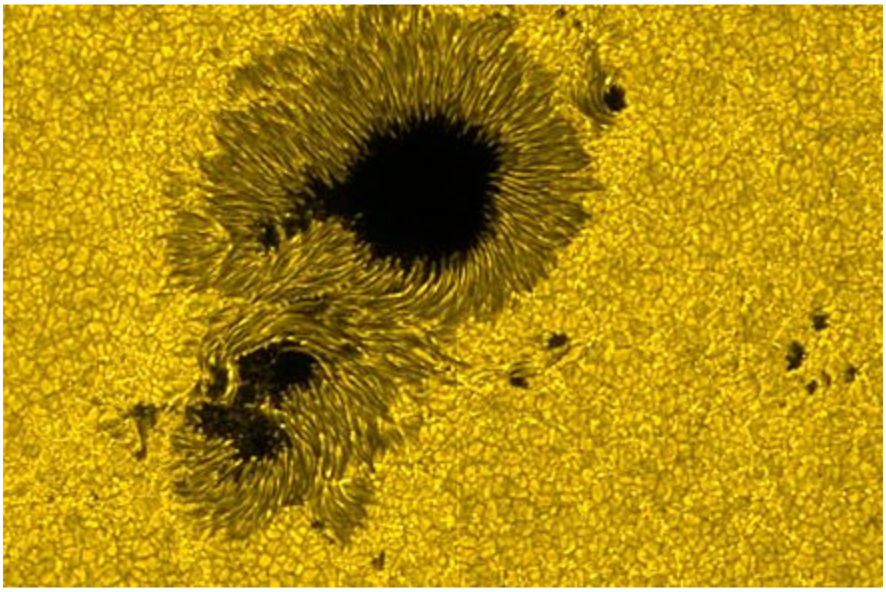


FIGURE 2. Nuclear fusion producing energy (Getty images 2018)

3.1.2 Sunspots

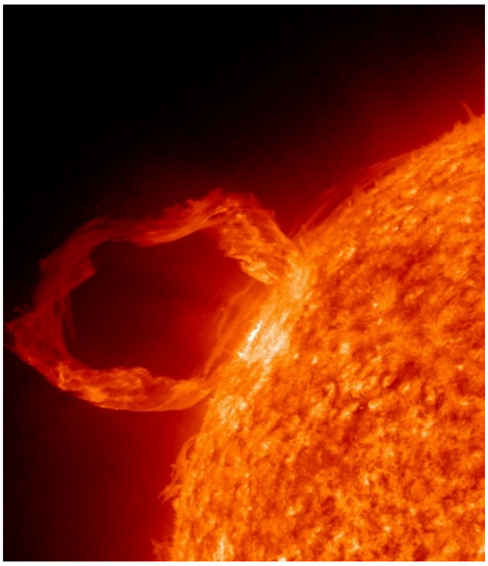
The heat given off by the Sun constantly stirs its outermost layers. The environment becomes unstable and turbulent movements begin. This is the phenomenon of convection. Convection is the set of movements generated in a liquid or gaseous fluid mass due to differences in density and temperature at various locations (Annaïg NK). Like the Earth, the Sun also rotates around its axis, in about 27 days, but unlike the Earth, its rotation is not uniform, the equator rotates faster than the regions near the poles. This unequal rotation, coupled with the phenomenon of convection, produces regions of intense magnetic field: sunspots. They usually appear in pairs of opposite magnetic polarity and represent regions of gas that are cooler than the surrounding gases (black spots on PICTURE 4). Sunspots are the seat of powerful magnetic phenomena on the surface of the Sun. However, they are not necessarily the cause of the aurora borealis. For a spot to be likely to form an aurora borealis, it needs an eruption and then a coronal mass ejection. (Foucher 2020.)



PICTURE 4. A group of sunspots (NASA)

3.1.3 Coronal Mass Ejection (CME)

Flares and then coronal mass ejections often originate from sunspots. These often form in pairs: one spot corresponds to a magnetic north pole, the other to the south pole. It then forms small and isolated filaments that can unite to form a very large and dense filament. These filaments become powerful magnetic arcs, around which plasma can aggregate after an eruption. When the magnetic field can no longer ensure the coherence of the arc, it breaks and will violently release all the plasma it contained into space: this is coronal mass ejection (PICTURE 5). This coronal material is ejected from the Sun at a speed close to 1000 km/s, mainly around the maximum of solar activity. This matter is made of ionized particles, of plasma, in much greater quantity than in the ambient solar wind. If released towards Earth, an aurora borealis may occur a few days later. (Foucher 2020.)



PICTURE 5. Coronal mass ejection (NASA)

Since the Sun has been observed and studied, it was found in 1850 that a peak in sunspot formation occurs every 11 years: This is the solar cycle (FIGURE 3). Thanks to this discovery, astrophysicists are able to predict the intensity of the Sun's activity. But even at the weakest of this solar cycle, it is quite possible to observe magnificent aurora borealis on Earth. They originate from the coronal holes, which appear very regularly on the surface of the Sun. (Foucher 2020.)

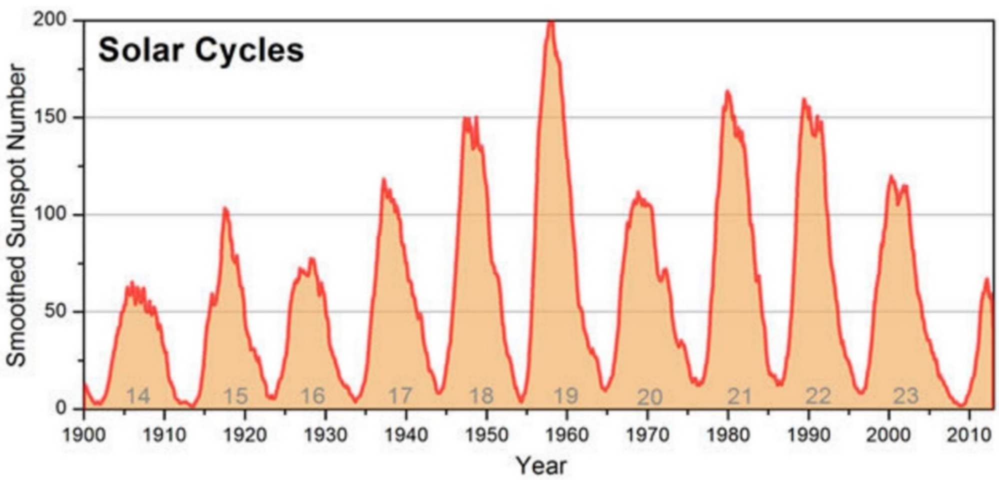
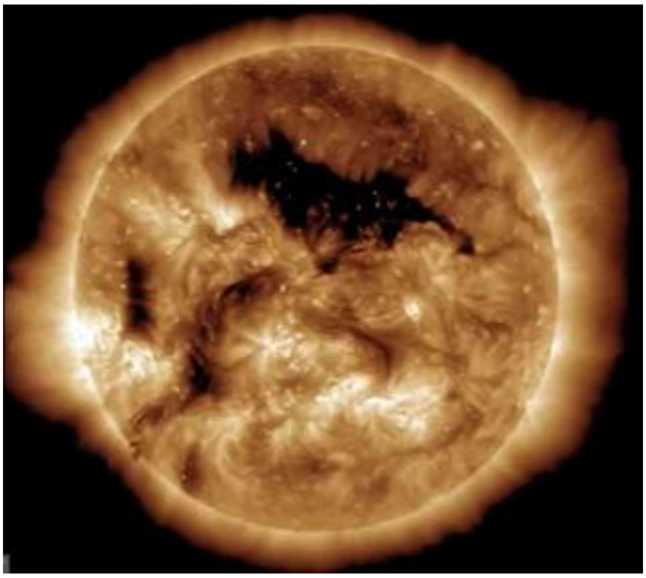


FIGURE 3. Solar cycle (NOAA 2020)

3.1.4 Coronal holes

Coronal holes are areas of low density where the lines of the Sun's magnetic field are open to space (black area on PICTURE 6). The solar plasma is then not retained, and a continuous stream is ejected towards space in the form of high-speed solar wind. The coronal holes are real open doors towards the interior of the Sun: they can also be at the origin of the aurora borealis if they face the Earth. (Foucher 2020.)



PICTURE 6. Coronal hole (NASA)

3.1.5 Solar Storm

A solar flare or solar storm is a primordial event in the activity of the Sun. Thus, a CME or a coronal hole causing high velocity plasma ejections through the solar wind are solar flares (or storms). Due to these plasma emissions, certain solar flares that reach the Earth can disrupt terrestrial radio transmissions (magnetic storm) and cause the appearance of the polar auroras by interacting with the Earth's magnetic field and the upper atmosphere. In FIGURE 4, the A represents the coronal mass ejections with sunspots at their bases, symbolized by black circles polarized + or -, while in B is the coronal holes directly open on space.

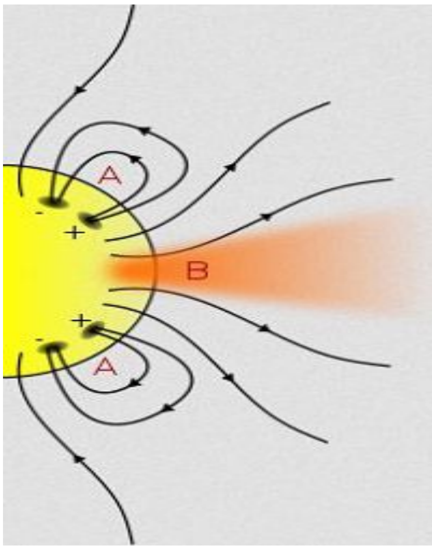


FIGURE 4. Coronal Mass Ejection (A) and coronal hole (B) letting escape a plasma flow from the Sun (Foucher 2020)

3.2 The Earth

The Earth is a gigantic magnet that generates its own magnetic field. Thanks to the difference in rotational speed between the planet and its liquid core, the Earth produces friction which generates a magnetic field called the magnetosphere. It surrounds and protects the Earth from external aggressions such as cosmic rays and energetic particles from the solar wind. But, like any magnet, it has a North pole and a South pole. The Magnetic North Pole is at the Geographic South Pole and the Magnetic South Pole is at the Geographic North Pole (FIGURE 5). (Gispert 2017.)

3.2.1 Geomagnetism

The Earth's magnet can be characterized by its field lines, which indicate in any place how the magnetic field is oriented. For a magnet shaped like the Earth, the field lines should be large curves going from the magnetic south pole to the magnetic north pole. On the surface of the Earth this is indeed the case, which is why a compass needle points to the magnetic North Pole. This remains true up to altitudes of the order of 1000 km. Beyond, the field lines begin to deform under the permanent action of the Solar wind. The pressure exerted by it (producing itself a magnetic field), crushes the lines on the day side (facing the Sun), and stretches them on the night side opposite the Sun. The stretch is large enough for the outer lines to open out into interplanetary space. The interior lines, less disturbed, remain closed.

The open lines start from the poles. This is what the THEMIS mission discovered in 2008. On the night side of the Earth, a hundred thousand km away, a magnetic reconnection occurs. This phenomenon is not yet fully understood, but during which disjointed magnetic field lines reconnect, producing heat or accelerating the particles present. Especially during solar storms, part of the solar wind is redirected towards the Earth's magnetic poles. The particles of the solar wind can thus descend to an altitude of 80 kilometers. (Kezako 2015.)

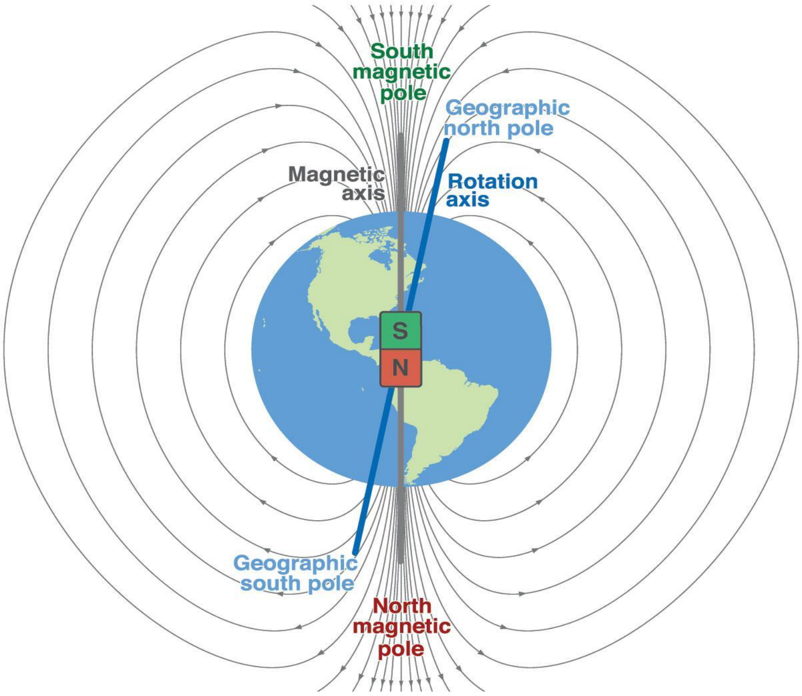


FIGURE 5. Magnetic poles VS Geographic poles (Getty images)

3.2.2 Earth’s atmosphere

The atmosphere is the gaseous envelope that surrounds the Earth. It is composed of 78% dinitrogen (N_2), 21% dioxygen (O_2) and other gases, including argon and carbon dioxide. These, combined with suspended particles, play a fundamental role in maintaining life: partial absorption of ultraviolet radiation, thermal buffer, or surface heating by greenhouse effect. Thus, between day and night, the temperatures fluctuate little. (Futura Sciences 2022.)

The atmosphere is made of four layers, and it is accepted that the altitude of 100 kilometers (the Karman limit) separates the atmosphere from space. Each layer is characterized by a different temperature gradient depending on the altitude: the troposphere (between 0 and about 15 km) is the first layer above the Earth's surface and contains about 85 to 90% of the mass total of the Earth's atmosphere. It is characterized by a drop in temperature with increasing altitude. The thermal profile of the troposphere largely results from the heating of the Earth's surface by incoming solar radiation. Heat is then transferred to the troposphere by a combination of convective and turbulent transfer. The weather occurs in the Earth's troposphere. (IASB NK.)

In the stratosphere (between about 15 and 50 km), the temperature increases with height. This warming results from the direct absorption of solar radiation by the ozone layer, thereby preventing much of the sun's harmful ultraviolet radiation from reaching the Earth's surface (FIGURE 6).

The mesosphere is the next layer of the atmosphere (from 50 to 90 km), characterized by temperatures that decrease as you go up to -90 ° C on average. Many meteors burn up in this layer as they enter the Earth's atmosphere. (IASB NK.)

Then, the thermosphere settles where temperatures increase steadily with altitude. It is the layer of the atmosphere that is exposed for the first time to solar radiation. The upper limit of the Earth's atmosphere is the exosphere where the atmosphere merges with space (FIGURE 6).

Auroras occur in a region of the atmosphere filled with charged particles called the ionosphere. It extends from 50 to 1000 kilometers above the surface, overlapping the mesosphere, the thermosphere, and the exosphere. At very high temperatures, the UV and X rays emitted by the Sun cause a dissociation of oxygen and nitrogen to form single atoms. But this radiation also causes ionization (loss of electrons) of these same atoms. A plasma is then observed, where the oxygen and nitrogen ions bathe in a “soup” of electrons: this is the ionosphere. (Foucher 2020.)

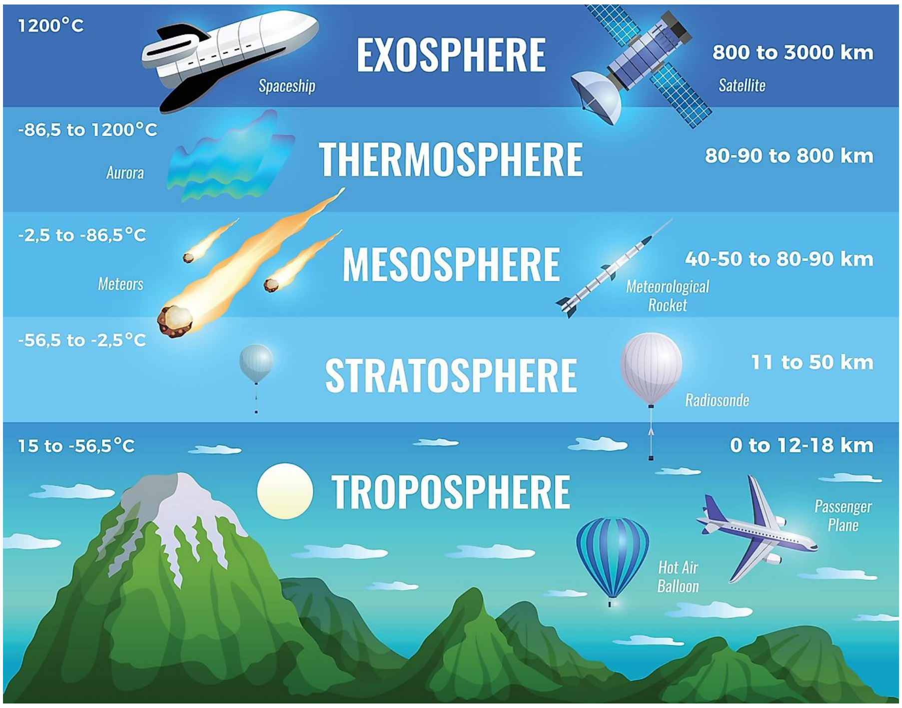
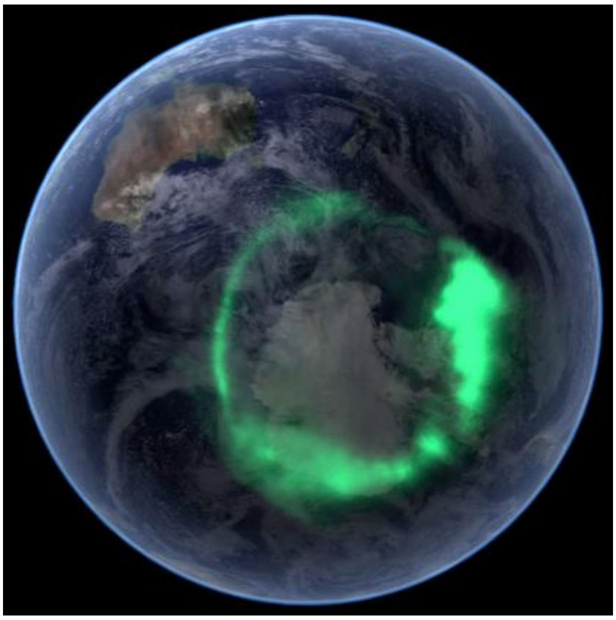


FIGURE 6. Layers of Earth's atmosphere (Čirjak 2020)

3.2.3 Auroral rings

The interactions between the particles of the solar wind and the Earth's field will come to form auroral ovals with a width varying from 500 to 1000 kilometers around the magnetic poles. These auroral ovals (or rings) represent the geographic location where the auroras primarily occur (PICTURE 7). The energy of the solar wind particles greatly influences the size of these rings. When it is weak (speed below 400 km/s), the auroral ring is of small diameter, and therefore the auroras occur near the magnetic poles. When the energy of the particles is greater, the rings enlarge, and descend towards lower latitudes. Therefore, in (rare) periods of very intense activity of the Sun, auroras are visible in France as far as Marseille. The intensity depends on many parameters, especially on the orientation of the solar magnetic field: when it is oriented in the opposite direction to the Earth's field, the magnetic phenomena are amplified, and the auroras as well. (Gispert 2017.)



PICTURE 7. The auroral oval of an aurora australis (NASA)

3.3 Northern lights formation

When a solar storm arrives on the magnetosphere (it is called a “magnetic storm”), two scenarios occur. At first the particles of the storm are engulfed by the polar cusp. This scenario cannot give rise to bright auroras because the base of the polar cusp is very narrow, and the magnetic field is there very strong. Very few particles therefore enter the ionosphere by this route. On the other hand, the base of the polar cusp is on the day side of the Earth, so it is not possible to see the aurora borealis shining there. (Foucher 2020.)

In the second scenario, the particle-laden solar wind is deflected by the Earth's magnetic field, pushing the plasma particles back into the night-side plasma sheet (FIGURE 7). The plasma sheet is separated into 2 parts (upper and lower) by a neutral sheet. During a strong solar storm, the plasma sheet will fill with charged particles, and under the pressure of the upper layers of the magnetosphere, the 2 plasma sheets will also stretch. These 2 combined effects will have the effect of compressing the neutral sheet. The lower and upper parts will then join, causing the phenomenon of magnetic reconnection. (Gispert 2017.)

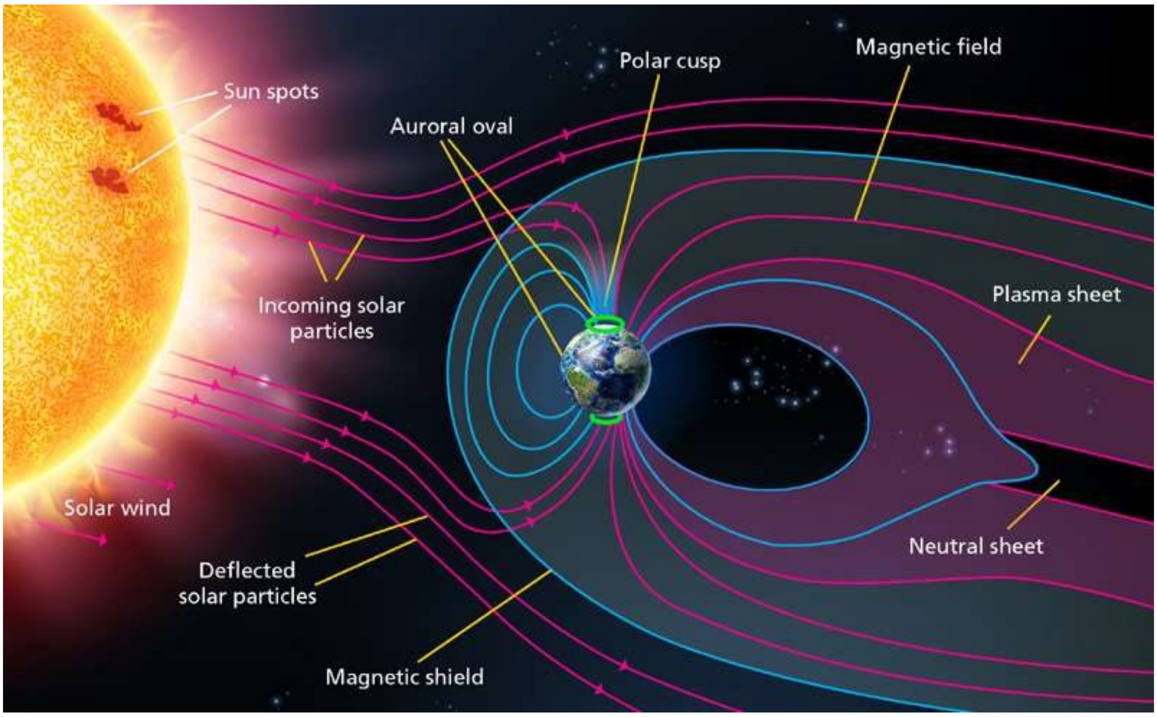


FIGURE 7. Northern Lights formation (Discover the world 2022)

This reconnection will catapult plasma particles towards the ionosphere: this is the “magnetic substorm”. As they pass through the upper atmosphere, they collide with the atoms there, including nitrogen and oxygen. This contribution of energy excites the atoms in high energy levels, and de-excites by emitting light: it is the aurora borealis and australis. The color emitted is specific to the excited atom, and as depending on the altitude, the oxygen and nitrogen concentrations change, therefore, the colors also change. From red at an altitude of 1000 km, the aurora turns green as it approaches the Earth at 250 km. Due to the deformation of the Earth's magnetic field, the particles are not exactly injected on the magnetic poles, but in the auroral zone, represented by the auroral ovals. (Kezako 2015.)

Finally, it may be necessary to specify that there can be a submagnetic storm even when no magnetic storm has arrived on Earth. The magnetic storm simply creates favorable conditions for a magnetic substorm to occur. It is therefore possible to observe the aurora borealis even in the absence of a solar storm. However, they will be less shiny and shorter. (Foucher 2020.)

4 COLORS AND SHAPES OF NORTHERN LIGHTS

The previous chapter explained that the atmosphere is made of different layers, and that these layers are more or less composed of the same gases but in different states. This chapter helps to understand the interaction of the ionized particles of the solar wind with the atoms of the Earth's atmosphere.

4.1 Colors of the Northern Lights

The aurora borealis is a natural physico-chemical phenomenon. Their appearance in the sky is the result of luminescence due to the de-excitation of molecules in the atmosphere. (Foucher 2020.) To better understand this phenomenon, it is necessary to understand fundamental principles of chemistry: the structure of the atom.

4.1.1 Bohr-Rutherford model

An atom is composed of three basic particles: protons, electrons, and neutrons. The nucleus at the center of the atom contains protons (positively charged) and neutrons (uncharged). The outermost regions of the atom contain the electrons (negatively charged) and orbit the nucleus. Atoms have different properties depending on the arrangement and number of their basic particles. (Zylberberg 2020.)

In 1911, Ernest Rutherford was the first to attribute a planetary structure to the atom: the electrons are separated by a vacuum and gravitate around the nucleus, like the planets around the solar system (FIGURE 8). But beware, the model described here has now been outdated by the principles of quantum mechanics and is only used for educational purposes. (Foucher 2020.)

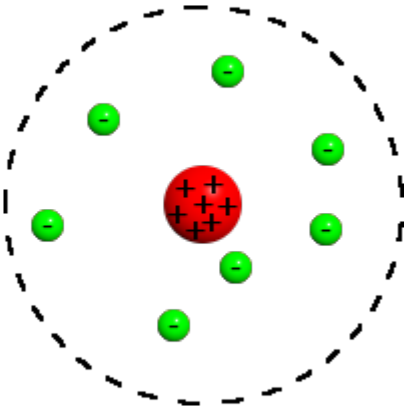


FIGURE 8. Representation of the Rutherford model of the nitrogen atom (Foucher 2020)

Two years later, Niels Bohr took Rutherford's model and adapted it by adding certain constraints: an electron can only be found in a well-defined orbit around the atom, which is called an electron layer; electrons cannot change layers unless they are excited; each of these layers has a specific number of electrons; and finally, a layer can only receive electrons if the previous one has been filled (FIGURE 9).

There are thus 7 different electron layers: the K layer represents the layer closest to the nucleus (level 1, the "fundamental" orbit), and the Q layer the furthest away (level 7). Each layer has an energy level noted "n". The lowest energy is that of the layer closest to the nucleus (layer K, n = 1), the highest is that of the layer furthest from the nucleus (layer Q, n = 7). (Foucher 2020.)

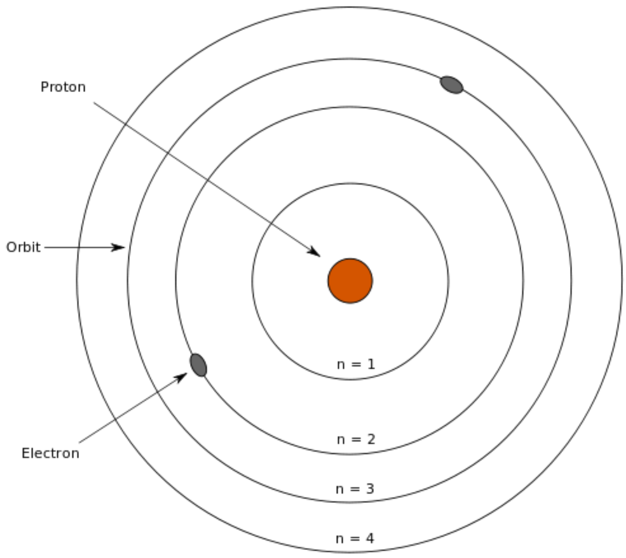


FIGURE 9. A schematic illustration of the Bohr model of the atom (Theopold 2020)

4.1.2 Luminescence phenomenon

According to Bohr, electrons can only be found in well-defined orbits around the nucleus of the atom and that they cannot change their orbits unless they are excited. If the energy supplied is sufficient and not too strong, Bohr specifies that the electron can change its orbit and go to a higher energy layer, and then return to its original position. But to return to its original position (a layer of lower energy level), the electron must release its excess energy in the form of a photon. The wavelength of the emitted photon will be specific to the return jump and to the excited atom. If the wavelength of the emitted photon is in the visible range (between 400 and 800 nm), then, a color can be perceived. (Beaumale 2017.)

An excited atom (one that has received extra energy) has seen one or more of its electrons change orbit. These electrons are in unstable states. In order for them to become stable again, the electrons can go back down one orbit, then a level of energy is lost, and a photon is emitted: this is the luminescence (FIGURE 8). Another possibility is to meet another element (atom or ion). In this case, the excess energy is transmitted to the encountered element, and no photon is emitted: it is the collisional deactivation (Foucher 2020).

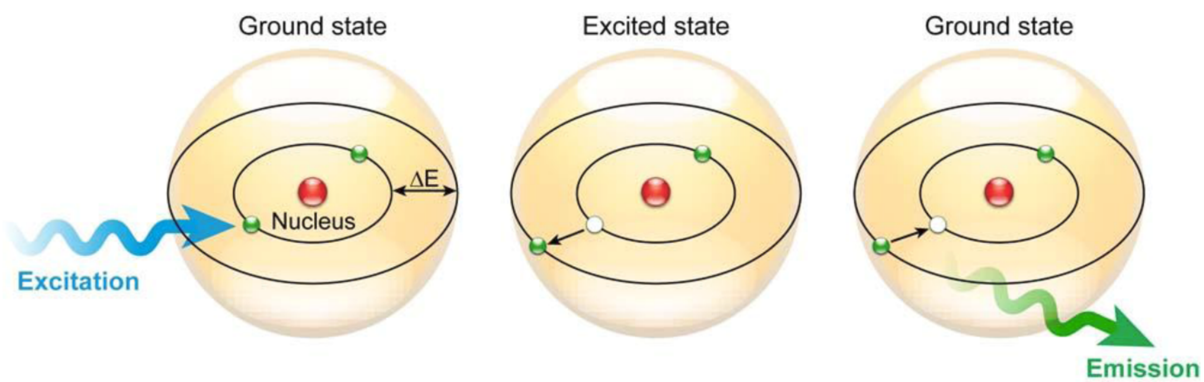


FIGURE 10. Schematic representation of the luminescence phenomenon in the classical Bohr model (MDPI)

4.1.3 Various colors available

All the elements are now gathered to understand how the color of the aurora is formed. They are often green in their lower parts, then red in their upper parts. This is due to the variation of atmospheric density and atmospheric composition, which is a function of altitude. (Beaumale 2017.)

Green auroras are the most common. They occur when charged particles collide with oxygen molecules in the middle layers of the ionosphere, between 100 and 300 km altitude. The atomic oxygen is predominant (the heavier oxygen is much lower). The electrons of the excited atom only have time to come down from their orbit once before being deactivated by another atom: they emit green light. (ASC 2021.)

Occasionally, the lower end of the aurora may be tinted pink or dark red. This phenomenon is due to the presence of nitrogen molecules, at about 100 km altitude. In the upper layers of the ionosphere, between 300 and 400 km altitude, the atmospheric density becomes very low. To such an extent that the electrons of oxygen have time to descend 2 orbits to stabilize completely (back on their fundamental orbits): they emit red. (ASC 2021.)

Blue violet can also appear at the top of the aurora: in this case, it comes from the excitation of hydrogen, ionized nitrogen, and ionized helium. These lighter gases than oxygen is only found in the highest layers of the atmosphere: a strong solar storm is required for them to be excited. However, these tints are difficult to perceive with the naked eye since they are difficult to distinguish from the black of the night sky. (ASC 2021.)

The composition of the low to medium altitude layers of the ionosphere is very varied: atomic oxygen, atomic nitrogen, or ionized nitrogen. Atomic nitrogen emits red, oxygen green and ionized nitrogen blue. If the solar wind particles have enough energy to reach these low layers before being stopped, a large palette of colors can be observed: pink, yellow, and white. (Foucher 2020.)

4.2 Shapes of auroras

There are different types of auroras, and each has a unique way of forming: the curtain, represents rays or lines of light. Auroras are bright and appear vertical. Seen from the side, they form compact spirals of light. The arc, on the other hand, is often formed before midnight. It consists of one or more arcs that extend from one end to the other of the horizon. The aurora in the form of spots appear during the recovery phase (after a substorm). These auroras can move, change in brightness and luminosity. Their diffusion area is relatively small. Other auroras appear as bands, this is the active phase of the aurora. The bands look like fragments of arcs. These bands can be calm, moving, or active. Finally, the corona, when viewed directly from below, the light appears to be cast in beams in all directions. (Beaumale 2017.)

4.3 Auroras on other planets

The aurora is not an Earth-specific phenomenon. They can be found on any planet with a magnetic field. The observation possibilities available to scientists today make it possible to accurately image the other planets of the solar system. Thanks to the ultraviolet photographs taken by the Hubble telescope, it is possible to obtain photos of the aurora on Saturn, Jupiter and even Mars, despite the weakness of its atmosphere. (Foucher 2020.)

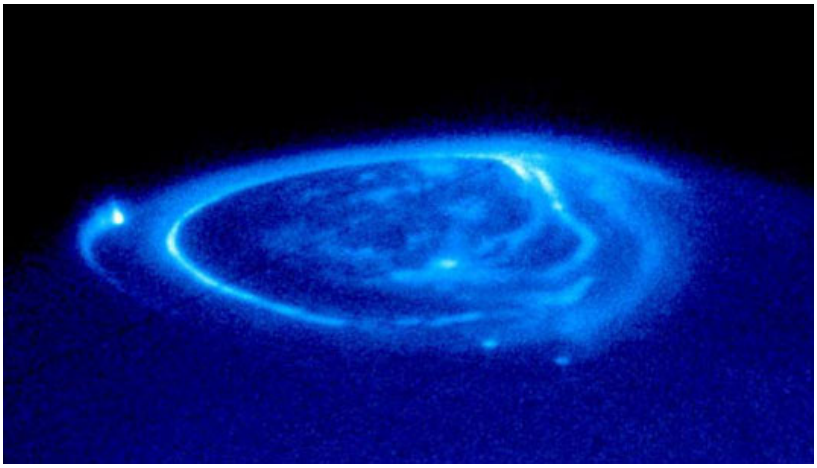
4.3.1 Mars

The case of Mars is different from that of the Earth. Mars has no actual magnetic field. However, it has a fossil field, fixed in the rock, as a memory of the time when it was active. This field is therefore not dipolar like the Earth, and its structure is much more complex. Also, as it can be easily visible on the PICTURE 8, auroras occur in the Red Planet's atmosphere, but their location is not as regular as one the blue planet. In addition, oxygen and nitrogen are very rare on Mars, so the auroras will not look the same. In fact, they have been observed in the ultraviolet, and probably do not occur in the visible. (Gispert 2017).

PICTURE 8. Aurora map on Mars (ESA)

4.3.2 Jupiter

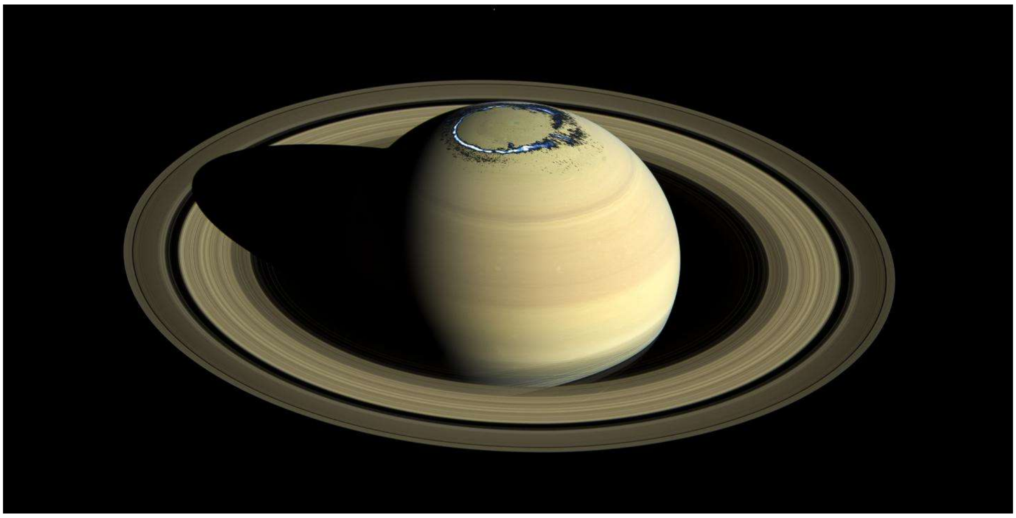
The PICTURE 9 of Jupiter makes it possible to perfectly distinguish the auroral ring, but some very bright spots are also present. These are auroras, but not produced by solar wind particles. On Jupiter, the natural satellites Io, Europa and Ganymede create an electric current as they move relative to the magnetic field. These currents create 'auroral spots', seen in UV in PICTURE 9 below. The particles are ionised and trapped by the planet's magnetic field. They produce a light 1 000 times more intense than that produced by solar particles. Consequently, if the aurora is always produced by particles colliding with the atmosphere, the origin of these particles can vary. (Fernandes 2022.)



PICTURE 9. Aurora on Jupiter (ESA/NASA)

4.3.3 Saturn

The aurora on Saturn is the result of the same phenomenon as on Earth. However, on Saturn, the auroras are generated by much more energetic particles, and are visible only in the ultraviolet because of the hydrogen-saturated atmosphere. They are also much more dynamic, with flashing and pulsating light phenomena. PICTURE 10 from Cassini in 2017 shows multiple parallel arcs near the surface, and an external light source of varying intensity. The latter could be caused by hot electrons ejected from its rings. Many mysteries remain to be unravelled about these Saturnian aurorae. (Deluzarche 2020.)



PICTURE 10. Recomposed image of a Saturn aurora from observations by the Cassini probe as it descended to the planet in August 2017 (NASA)

5 DETECTING THE APPEARANCE OF THE AURORA BOREALIS

Today, it is possible to predict future auroras. A NASA satellite called SOHO (Solar and Heliospheric Observatory) is orbiting the sun, constantly inspecting it. The satellite captures images of solar flares and coronal holes and sends them to Earth. This allows professionals to predict when the polar aurora will appear. However, even if the aurora is visible to the naked eye, being in a suitable area (auroral oval) is not enough. Seeing an aurora depends on three other factors: the cloudiness, light pollution, and Kp index. (Gillet 2016).

5.1 Cloudiness

The weather conditions of the location are important. For example, if the weather is not good (fog, heavy rain, thunderstorms, heavy snowfall) the visibility will be reduced and therefore the probability of seeing auroras will be decreased. As explained in Chapter 3, auroras are located well above the clouds, so a heavy sky is not suitable for their visualization. Areas where there are significant anticyclones (synonymous with clear skies and dry weather) are where aurora visibility will be amplified. (Gillet 2016.)

5.2 Light pollution

The light pollution of the location is also important. Indeed, if the space is strongly lit (in a big city or in a port for example), the polar auroras are more difficult to see. On the other hand, the brightness of the Moon, especially during the full moon can also reduce the visibility of these phenomena, which, remember it, are only luminous. (Gillet 2016.)

5.3 Kp Index

The Kp index is the last factor to be considered to detect the aurora. This index, called planetary k-index (k for the German term *Kennziffer* meaning significant number) allows to measure the geomagnetic activity of a magnetic field (and more particularly of the terrestrial magnetic field). This activity corresponds to the degree of disturbance of a magnetic field (i.e., the presence and intensity of magnetic storms that run through it). (Gillet 2016.)

This index has a numerical value between 0 and 9. The geomagnetic activity of the Earth is measured using information from the SOHO satellite, then after a period of 3 hours an index is obtained. If the Kp index is less than 5, there is no or a very weak magnetic storm and there will be a weak presence of aurora. If the index is between 5 and 7, there is a magnetic storm of medium intensity and there will be a medium presence of auroras. Finally, if the index is between 7 and 9, there is a magnetic storm of strong intensity and there will be a significant presence of auroras. (Gillet 2016.)

From data collected according to different intensities of disturbances of the Earth's magnetic field, scientists have established a map of Kp lines (FIGURE 11). Thus, the corresponding line to the current Kp index can be read on the map, and auroras will take place on a latitude zone higher than the Kp line. For example, if the Kp index is 5, it will be necessary to be above the Kp = 5 line (green), thus in the Scandinavian countries, to hope to see an aurora. (Gillet 2016.)

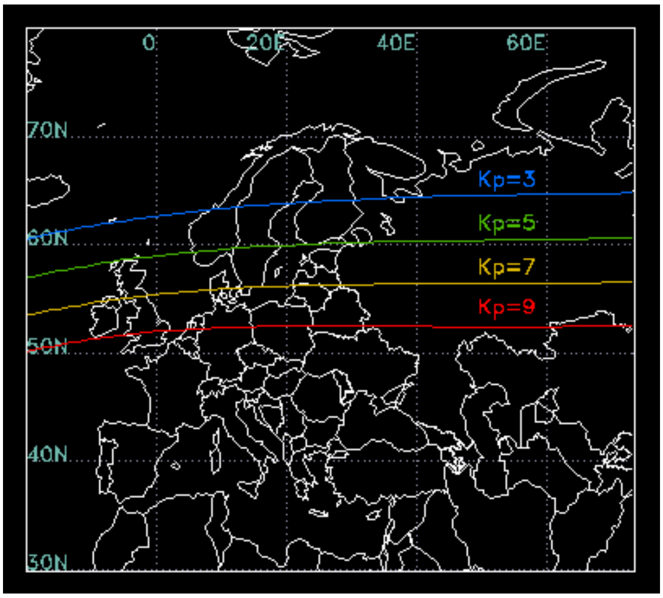


FIGURE 11. Map of Kp lines (NOAA)

6 PREDICTING THE APPEARANCE OF THE AURORA BOREALIS

Although in recent years the understanding of the functioning of the Sun has evolved well, it is not yet possible to predict its activity, nor its projections of matter into space, but they can be monitored. Indeed, the monitoring of the solar activity makes it possible to predict the arrival of a cloud of matter in direction of the Earth, even of a storm. This can provide crucial information in many situations: these clouds charged with energy can interfere with radio signals (communications, GPS), disrupt electricity networks to the point of "frying" them or even damage space satellites. These predictions are therefore useful not only for predicting potential auroras in the sky, but also for airlines, satellite operators, and power grid operators. The Sun is therefore permanently monitored by satellites of different programs and from observatories on Earth.

The main satellite used is SOHO. Launched on December 2, 1995, SOHO was placed between the Earth and the Sun at a very specific point in space: at the Lagrange L1 point, the point of equilibrium of the gravitational forces of the Sun and the Earth at 1 500 000 km from the Earth. Although having a smaller orbit than the Earth, the satellite rotates around the Sun at the same time as the Earth, and with the same angular speed. Being placed before the solar wind, SOHO is confronted to the solar wind and its plasma projections well before the Earth. Its various sensors analyze the different characteristics of the solar wind (speed, density, electric charge, electro-magnetic field intensity), then it sends its information by radio communications, received in turn by the 3 centers of the DSN (Deep Space Network). These centers are based equidistant from each other, in Madrid (Spain), Goldstone (California) and near Canberra (Australia) and allow continuous communication with some distant satellites despite the rotation of the Earth. (Aurora-maniacs NK.)

The information sent by SOHO by radio waves propagates in space towards the Earth at the speed of light (nearly 300,000 kilometers per second), much faster than the speed of the solar wind. This allows scientists to know 30 minutes in advance (the time it takes for clouds of particles to reach planet Earth after passing SOHO, time which varies with the speed of the solar wind) what the Earth will receive. This information is collected and analyzed, mainly by the National Oceanic and Atmospheric Administration (NOAA), which then provides information on near-Earth space weather. This can potentially be very useful for preparing for large geomagnetic storms, but especially for monitoring auroral activity and the chances of observing auroras. (Aurora-maniacs NK).

The 2 other main satellites used are STEREO A (Ahead) and STEREO B (Behind), from the Solar Terrestrial Relations Observatory program. They allow the observation of the ejections and the propagation of matter in space and their follow-up. These two satellites are placed on the orbit of the Earth around the Sun: one upstream, the other downstream. Their spacing allows three-dimensional observation of particle clouds, facilitating their positioning and evolution. Since 2014, Stereo B has been out of service.
Other satellites are also involved in monitoring solar winds and their impacts on the Earth and its surroundings. (Aurora-maniacs NK.)

In 2024, before the peak of the 25th solar cycle, NOAA will launch into space a new satellite called SWFO-L1 (Space Weather Follow-On) which will have the mission to observe coronal mass ejections and analyze solar winds. It will also be positioned at the Lagrange L1 point. It will help to improve the observation and forecasting of solar activity, the DSCOVR (Deep Space Climate Observatory) missions of NOAA launched in 2015 and the joint mission of ESA (European Space Agency) and NASA launched in 1995. There are other observing missions, whose data are provided by other satellites or sensors on Earth. All these measurements are mainly processed by NOAA, which provides useful and understandable information: density, size, and charge of the clouds of matter, speed of movement, and direction. It is therefore possible to estimate approximately when the solar winds will arrive on Earth. (Aurora-maniacs NK.)

Despite all these tools, it is not possible to predict with precision the presence of an aurora borealis, its position, its intensity, its size, nor even its duration of visibility. But the information provided is sufficient to have an idea of what should happen in the sky.

7 CONCLUSION

Since the birth of humanity, the polar auroras have played an important role, fascinating or frightening the populations. Sources of multiple legends and ancestral superstitions, the thesis focused on the aurora borealis rather than the aurora australis, since the populations and therefore the potential observers are essentially present in the Arctic. For a long time assimilated to supernatural phenomena, humans have been able, over the centuries, to prove that these phenomena had nothing divine but everything physical. It was not until the 18th century that Birkeland realized a device allowing to recreate auroras. Indeed, the way in which they were formed was then proven in a scientific way thanks to the development of technologies and to the many discoveries with the wire of the centuries allowing to make science more precise. The phenomenon of polar auroras, although appearing on Earth in a magnificent way, initially starts within a star: the Sun. It is therefore not surprising that this physical phenomenon can also be present on other planets of the solar system.

The Sun permanently emits a solar wind made of charged particles and ionized gas called plasma. Mainly emitted during solar flares, it propagates at high speed in the solar system. This solar wind is however slowed down by the Earth's magnetic field, a real shield that allows life on Earth. Most of these particles are diverted by the lines of the Earth's field and stored in a huge reservoir on the night side. During magnetic substorms, these very energetic particles are propelled towards the magnetic poles of the Earth. Upon entering the ionosphere, some of them will meet oxygen, nitrogen or, more rarely, hydrogen, forcing some electrons to move to a higher energy level. By returning to their fundamental state, they emit a photon of a certain wavelength. The denser and more energetic the flow of particles is, the more varied the colors and the more intense the aurora borealis will be.

This thesis made it possible to understand that the aurora borealis involved very complex physical and chemical phenomena, both at the atomic and macroscopic level. Detecting the northern lights is not so easy and requires a lot of patience. As for their prediction, despite the technologies available to the 21st century today, accurately predicting the arrival of this phenomenon remains a very complicated task.

Finally, the writing of this thesis has made it possible to deepen knowledge in astronomy and to enrich the scientific vocabulary that this discipline requires. The interview of specialists such as the scientists of the Meteorological Institute of Helsinki could have brought more material to this thesis but unfortunately the necessary conditions for this interview could not be met. However, this trip to Finland will have been worth it: a polar aurora is surely one of the most beautiful phenomena that one can see on Earth.

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