The Aurora Borealis

By:
Micah Wyssmann

Physics II
Lab Section H3
Spring 2011

Date Submitted: April 25, 2011

Aurora Borealis is a Latin term, which roughly translates as Northern Lights, that has been attributed to the phenomenon of light occurring in the Earth's atmosphere in the northern hemisphere, most frequently in its upper reaches. Pierre Gassendi is often credited with naming this phenomenon the Aurora Borealis, but if the writings of Gassendi and also Galileo Galilei are thoroughly examined, it is clear that the credit for this term should go to Galileo or possibly his student Guiducci but not to Gassendi (Eather 1980, 51). Along with Gassendi and Gailieo, many other significant scientists and historical figures wrote about the northern lights: Aristotle, Leonard Euler, Anders Celsius and many others (Chapman 1967, 15-17). The Aurora Borealis, as we now know, is the result of solar wind that enters the Earth's atmosphere, exciting atoms within and causing them to release the photons that are seen in an event. This paper will discuss the history of the Aurora Borealis as well as discuss the physical reasons that explain the occurrence of this phenomenon.

The human race, or at least portions of it, has been aware of the phenomenon called the Aurora Borealis for a great span of time. Historical scholars believe that the first recorded sighting of the Aurora lies within the early Babylonian astronomical texts; in the year of 567 BC, these texts reported a red glow in the sky that lasted for a 24-hour period. There is also a supposed report of the Aurora in the book of Ezekiel chapter 1, but the interpretation of the year of this event, at 593 BC, is speculative as is interpreting the imagery used in the description as a geophysical event (Stephenson, Willis and Halinan 2004, 6.15-6.17). These two are the first supposed reports of the Aurora, but after this came more accounts by different figures. Aristotle discussed the Aurora in his work *Meteorologica* and referred to it as a great fire in the sky, believing it to be related to comets and shooting stars (Hackman 1995, 36). Other writers mentioned auroras in their works, including Anaximenes, Seneca, Cicero and Pliny the Elder.

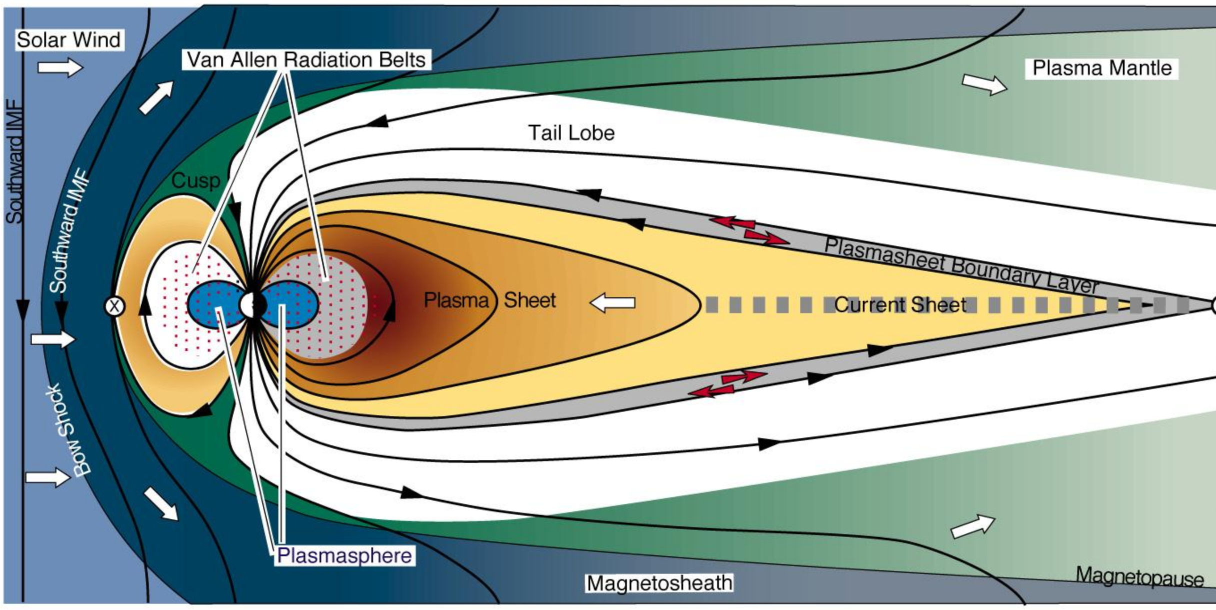
These are the earliest reported viewings of auroras and range in time from the first in 567 BC to around 300 BC.

While we have these early reports of auroras, it was not until Pierre Gassendi wrote about the display of the Aurora Borealis on September 12, 1621 that the Aurora was viewed in a scientific light. About a century later Edmond Halley also wrote a scientific report on an aurora he had seen on March 6, 1716. Based on his observations of this and another aurora in 1719, Halley devised a theory that the aurora was caused by a flow of magnetic particles along field lines, which he drew very similar to those of a magnetic dipole, that interact with the air to cause the luminescent display that is the aurora. Halley used steel filings to draw a diagram of the magnetic field lines that he believed these particles followed and this diagram resembled the field of a magnetic dipole, which was information that he had touched upon long before its time (Chapman 1967, 15-16). His theory was not the only one, however, and the theory of Jean Jacques d'Ortous de Mairan's hypothesis that the aurora was the result of the sun penetrating the atmosphere of the earth was largely popular during his time (Hackman 1995, 37). Although his hypothesis was completely incorrect, it was de Mairan who wrote the first treatise devoted to the aurora in which he discussed a method of determining the height and location of an auroral arc as well as the theories of other scientists such as Graham and Celsius (Chapman 1967, 17). In addition to this work, de Mairan was also one of the first to catalogue auroral events, along with John Dalton, Hermann Fritz and others; these methodical observations of the Aurora Borealis were also significant in prompting scientific evaluation of the aurora (Chapman 1955, 2).

Aside from de Mairan and Halley, many other theories were proposed and were either disproved altogether or simply contributed to and stimulated further theories that have led to the theory that is now confirmed by massive amounts of research. One of the major milestones in the developing an explanation of the Aurora Borealis was a theory proposed by Kristian Birkeland and Carl Störmer. This theory says that energized particles from solar wind could enter the Earth's atmosphere in regions called auroral zones and would then interact with atoms in the atmosphere to produce the luminous phenomenon. Now we know that this theory was very close to correct, but the development of theories concerning the magnetosphere, which came around 1930, was needed for the solar wind theory to be proved true. In 1950 the theory was finally proven that the visual effects of the aurora were generated by energetic particles entering into the Earth's atmosphere and colliding with other particles within (Chapman 1967, 23).

In order to understand the physical properties of the Aurora Borealis, one of the first concepts that must be explained is the magnetosphere. The center of the Earth is made up of a liquid metal conducting core, which creates a magnetic field with a magnetic moment of $8\times10^{15}Tm^{3}$. The magnetic field from this conducting core is not allowed to resemble a dipole magnet on a macroscopic scale, however, because solar wind, a plasma made up of mostly protons and electrons, is emitted by the sun and places pressure on this field (Russel 2000, 1818). The pressure from this solar wind causes the magnetic field on the side facing the sun to compress, while the magnetic field on the night side of the earth is elongated such that the total magnetic field resembles a comet as shown in Figure 1; we call this region the magnetosphere. At the edge of this region is what is called the magnetopause, which is a sharp boundary between the magnetosphere and solar wind (Hargreaves 1992, 4). The entire magnetosphere and especially this region of the magnetopause help to block solar wind from entering into the earth's atmosphere. There are regions, however, where the magnetosphere and the magnetic field created by solar wind, called interplanetary magnetic field (IMF), interact. Figure 1 shows how when the IMF is pointed southward it connects with the magnetic field of the earth in what is

Figure 1: The Magnetosphere



http://space.rice.edu/IMAGE/livefrom/sunearth.html

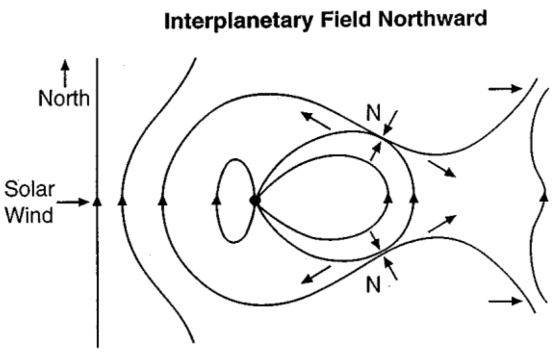


Figure 2
(Russel 2000, 1824)

called reconnection. Although most representations of the magnetosphere make the assumption that IMF is directed southward it can also direct northward and produce a magnetosphere that would, if reconnection occurred, have cusps in different locations, as shown in Figure 2 (Russel 2000, 1823-1824). In discussing the Aurora Borealis, though, the structure as the IMF is directed southward is of primary concern.

For an aurora to be created, energetic particles from solar wind must interact with atoms within the atmosphere, which means that they must first pass through the magnetosphere; the physical reasons that explain why the particles are able to pass through the magnetosphere are still debated among scientists, but a few of the theories and the points that are universally accepted will be outlined here. First, the most universally accepted fact about how solar wind particles enter the magnetosphere is that the levels of solar wind must be greatly elevated. It was first believed that solar flares were major the source of the increase in solar wind that created auroras, but coronal mass ejections (CMEs) are now credited as the primary source while still a few are caused by coronal holes and solar flares (Burtnyk 2000, 36-37). Concerning the entry of the solar wind into the magnetosphere, one theory is that as the solar wind hits the magnetopause it experiences a Lorentz force ($q\vec{v} \times \vec{B}$) due to the magnetic field and creates a current within, a small portion of which follows the IMF lines into the atmosphere (Akasofu 1979, 229-230). Another more recent theory is that it is in the process of reconnection the Earth's magnetic field lines and the IMF lines cancel to create a break in the magnetosphere that allows the plasma to enter into the atmosphere. Also noteworthy, this process of reconnection is believed to release a great amount of energy and excite the particles (Burtnyk 2000, 38). There are other theories, one such concerning the coupling of the Magnetosphere and Ionosphere (Russel 2000, 1825), but the fact researchers agree upon is that once the particles from the solar wind are within the magnetosphere they form a plasma sheet, shown in Figure 3, on the side of the earth away from the sun (Baranoski et al. 2000, 4). Once the energetic particles from the solar wind have reached this plasma sheet, scientists know that the force that drives

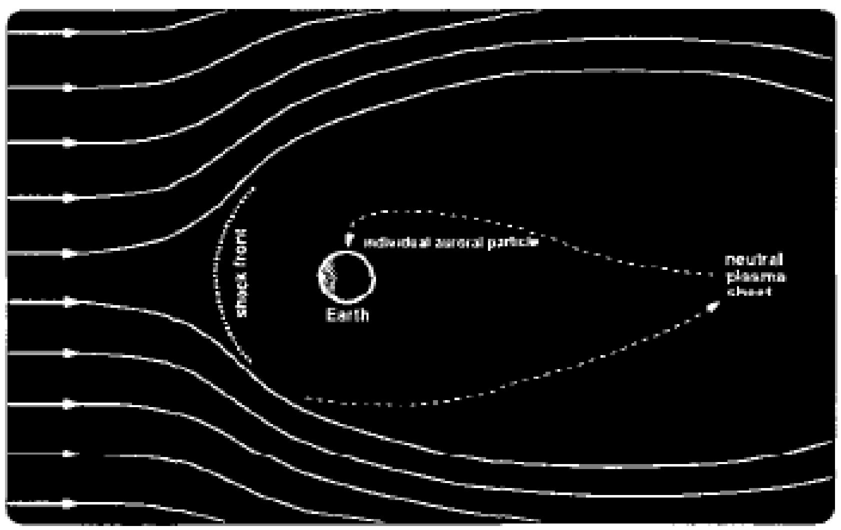


Figure 3
(Baranoski et al. 2000, 4)

them into the Earth's atmosphere to create the Aurora Borealis is the result of the large electric fields created within the magnetosphere by the process of reconnection (Burtnyk 2000, 39).

Once the energetic particles from solar wind have made their way into the Earth's atmosphere, they then interact with and excite atoms from the air, which then emit the photons that make up the visual phenomenon named the Aurora Borealis. One of the types of atoms that the energetic particles interact with in the atmosphere is atomic oxygen; this interaction does not produce one color every time, however, but will release a photon of green or red color (Lummerzheim 2010). The other type of atom in the atmosphere that these particles interact with is ionized nitrogen, which can emit various colors including blue, purple or red based on the ionization of the molecule and the altitude at which it is excited (Burtnyk 2000, 40). In order to understand the different photon emissions of oxygen atoms as well as the arrangement the colors at different altitudes, there are a few facts that must first be understood. One of these facts is that, after an atom is excited by the energetic particles, there is a span of time that elapses before a photon is actually released from the atom; also, the time that it takes for the photon to be released from the atom is different for each emission type. These facts are understood to be relevant to emission type and placement in the atmosphere by coupling them with a process that occurs called quenching, which causes an excited atom to lose its ability to release a photon if it collides with another particle before it has the opportunity to do so (Baranoski et al. 2000, 5). Now a single oxygen atom can release both a green and a red photon after being excited by a solar wind particle, but these emissions will occur at different times. This is because a photon is released only when an excited atom lowers an energy level, and oxygen atoms will most often be excited two levels above their normal when excited by energetic particles. The oxygen atom will release a green photon as it drops one energy level from the second above its normal and will release a red photon as it then returns back to its normal energy state. The time it takes for each of these energy level changes, however, are very different since the first drop takes less than a second, while the second drop takes almost two minutes (Burtnyk 2000, 39-40). Synthesizing this array of information, it is understood that the green portions of the Aurora Borealis would occur lower in the Earth's atmosphere than the red portions, which is an observed fact, because the atoms would need the extra space between particles provided higher in the atmosphere to be able release the second photon without being quenched (Burtnyk 2000, 40). These facts generally characterize the Aurora Borealis and scientists assign a type to each auroral event, which is based on the arrangement of colors within, for the sake of analysis but, while this is effective for the specific purpose, each aurora has a very individual nature and cannot be specifically defined by generalities (Chamberlain 1961, 125).

In addition to having a certain color makeup, the Aurora Borealis is also often arranged in certain patterns that have been recorded, analyzed and categorized; as with the color of the aurora, though, these classifications are by no means absolutes regarding this natural phenomenon. Before analyzing individual classifications that are at times based on perspective, however, it should be noted that the aurora always has the general form of a curtain on a macroscopic level because the energetic particles are confined to travel along the curved magnetic field lines of the Earth, even when they collide with other particles to create the aurora (Lummerzheim 2010). The most basic auroral classification that scientists note is that of light that has no structure or possibly small cloud-like

Figure 4: Homogenous Arc
http://www2.gi.alaska.edu/asahi/aurforms.htm

groupings (Angot 1897, 12). A homogenous arc is a form of the aurora that has much more specific and noticeable descriptions; these tend to stretch from magnetic east to west and have a definite lower boundary but fades as it extends upward as the photograph in Figure 4 shows (Chamberlain 1961, 117). These arcs are usually almost motionless and tend to stay still in the sky for hours or possibly longer (Angot 1897, 21). Homogenous bands are very similar to homogenous arcs, but they are less definite in their shape and seem to have motion whereas the arc stays still. In combination with these more specific outlines, there are a few classifications of the appearance of the Aurora Borealis are independent of this type arc or band structure but demonstrate certain characteristics of an aurora. One such classification concerns whether the auroral form is pulsating, which can be applied to arcs and bands as well as to the undefined surfaces that resemble clouds at times. The other classification is whether the auroral form has a ray structure, which simply determines if there are vertical striations in the structure, such as the rayed arc displayed in Figure 5.

Figure 5: Rayed Arc
http://www2.gi.alaska.edu/asahi/aurforms.htm

Figure 6: Corona
http://www2.gi.alaska.edu/asahi/aurforms.htm

There is, however, the possibility that the aurora will have individual rays or groups of rays that are independent and not just an added characteristic to an already existing form (Chamberlain 1961, 117). The last form to be discussed here is the corona, showed in Figure 6, which has a very specific form to the viewer but which is completely created based on the perspective the aurora is viewed from. The corona form is seen when individual portions of a rayed aurora appear, because of perspective, to converge toward a specific point even though they do not actually do so (Asahi Aurora 2003). These are some of the more definite forms of the Aurora Borealis that have been given classification, but the phenomenon does not always resemble one of these structures and, especially when the aurora is strong, the sky can simply be a jumble of auroral lights that are of an indistinguishable form (Chamberlain 1961, 124).

Developing a sense of where the Aurora Borealis occurs is a task that is difficult due to the many and varied events that are attributed to it, but scientists have discovered much about the location of the phenomenon. Concerning altitude, it is and has been known for some time that the aurora occurs within the region of 100 to 1,000 km (Chapman 1967, 22). However, it is now believed that the majority of the visible portion of the aurora is generated between altitudes of 100 and 300 km (Baranoski et al. 2000, 4). The green portion of the aurora emitted from the oxygen is believed to occur at the lower altitudes of this range (Baranoski et al. 2000, 5). Also, the nitrogen emissions are believed to occur mostly at the bottom of this range and, some believe, possibly even lower near an altitude of 80 km if the solar wind is able to reach that level (Burtnyk 2000, 40). Concerning global position, scientists have discovered that auroral events occur in regions encircling the geomagnetic poles. Based on the correspondence of the many records of the events of the Aurora Borealis, it has been determined that the area of greatest frequency for auroral events, called the auroral zone, is about 20˚ to 25˚ latitude from the geomagnetic pole. Generally, the Aurora Borealis occurs primarily in the auroral zone and also in the auroral cap, the polar region enclosed by the auroral zone; there are significant historical reports of the Aurora Borealis in much lower latitudes, though, such as the accounts mentioned earlier that were written by Aristotle, Pliny the Elder and Seneca. Since there is so little record of the events occurring far out of the auroral regions, however, it is not possible to determine the frequency of such events (Chamberlain 1961, 101-104).

One intriguing question concerning the Aurora Borealis that has hung in the balance for centuries and scientists have yet to either prove or disprove is whether the phenomenon creates sound. This question does not seem pressing to many scientists but it is still an unanswered question that concerns the physical results of the auroral phenomenon the same as many other research questions. When looking for proof of auroral audibility, there is almost none to be found that has been obtained through physical measurement by audio instruments; this is the reason that auroral audibility has yet to be definitively proven and why many believe that the phenomena does not create sound. The only audio recording of what could possibly be sound coming from the aurora was recorded with a hasty and untested setup so that the results cannot be used to draw any conclusion. No other recordings have been made, partially because this not many are attempting this and also that the prospect of obtaining a recording of auroral sounds while eliminating all other ambient noises is daunting in the least (Laine 2004, 3-5).

Although there is no proof obtained by audio instruments that there is sound emitted from the Aurora Borealis, an analysis of data obtained based upon first-hand accounts seemingly balances the lack of physical evidence so that the question of auroral audibility rests quietly yet stubbornly at equilibrium, despite all attempts to tip its scales. In the late 19th century, Sophus Tromholt sent inquiries to many people asking if they or people they knew of had heard any sound from the aurora and if so what kind; in response he received 20 notices of denial and 92 of confirmation. The replies of confirmation all reported similar sounds such as a whispering, crackling, hissing, rushing, or other noises of the sort (Beals 1993, 185). C. S. Beals describes many more events that resemble this one in the fact that completely independent first-hand accounts confirmed an auroral sound and with similar descriptions. The methods used in collecting the data in these cases could be described as scientific, but the results are still too objective because they are based on human perceptions. The connection that must exist between these two seemingly contradictory evidence groups has yet to be discovered. Some scientists believe that if we find this connection it will have to do with the human psyche and how we perceive a sight such as the aurora and nothing to do with the aurora itself (Lummerzheim 2010). Nevertheless, the question of auroral audibility is still without an incontrovertible answer and remains one of the many mysteries that surround this phenomenon.

The Aurora Borealis is a complicated phenomenon that has many physical aspects that must be considered in order to understand it, even to the level that current scientific knowledge allows. If we are to ever completely understand this phenomenon, though, there are many questions scientists must first answer as well as they must expand and flesh out present explanations of even the basic questions. One of the largest parts of the process that creates the aurora that is still not understood is how solar wind is able to enter into the magnetosphere. We know this has to do with reconnection of the IMF with the Earth's magnetic field, but we are unsure of the specifics of this interaction that allow the energetic particles to pass through the magnetopause. There are also interesting things that occur in the aurora itself that we do not yet understand, such as why there are electric fields created in auroral substorms. In the 20th century we also became aware of the effect the aurora had on radio waves and have since begun researching this matter, which we call the radio aurora (Lange-Hesse 1967, 519). These topics as well as others must be discussed and researched if the goal of understanding this phenomenon is to be met. This paper has outlined the history of human knowledge of the Aurora Borealis and discussed the knowledge we have obtained as well as some of the questions about this phenomenon that still remain.

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