The Aurora Borealis: Mechanisms, Locations, and Variations

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Our Sun is a beautiful and dynamic star that allows life to flourish on Earth by providing light, heat, and energy. Despite its beauty, it can also be detrimental to our technologically reliant society through solar events, such as flares, coronal mass ejections, and solar wind. Its energetic plasma and radiation interact with Earth's magnetosphere and everything within, like satellites, astronauts, and power grids. This interaction is known as space weather, and two of the amazing results are viewed in the Northern and Southern Hemispheres, as the Aurora Borealis and Aurora Australis respectively. They are certainly a wonder to see in person and should be on everyone's bucket list. So, how do these lights form? Why are they typically seen around the polar regions? And what is the auroral oval? This article aims to present an overall examination of the connectedness between the Sun and Earth in the field of space weather via this light show through magnetic reconnection events, currents in the magnetosphere, aurora classification, and the latest research.

Earth's magnetosphere is a wonderfully complex entity that protects our infrastructure and life from the Sun's harmful radiation. Auroral processes begin when the Sun's plasma interacts with our magnetic field. If the plasma's magnetic direction is predominately southward, it will be attracted to Earth's northward magnetic flow. Charged particles (protons, electrons, and ions) connect with our magnetic field lines and break them apart on the dayside. This connection accelerates these particles along the lines, down towards the poles producing daytime auroras, which can only be observed through special ultraviolet filters. The solar pressure continues to push back the field lines to the night side, where they reconnect and again accelerate the particles back towards the poles to produce the nighttime auroras. These two connection events indicated by the boxes in Figure 1 are known as magnetic reconnection.

Figure 1

Illustration of Earth's magnetic field with the two MMS areas of study outlined

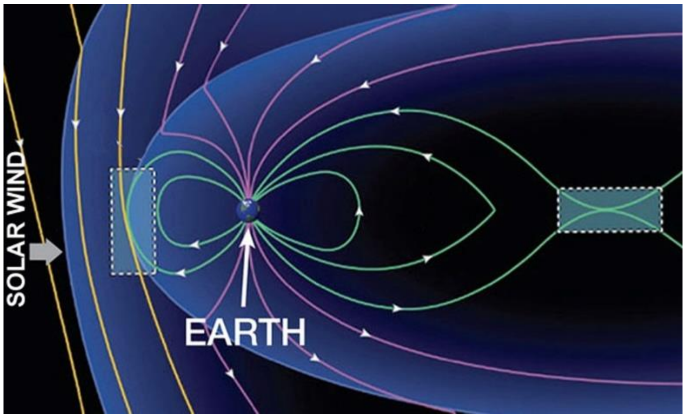

Image Credit: NASA

They are a powerful occurrence where magnetic energy is transferred "into heat and energy in the form of charged particle acceleration and large-scale flows of matter" (Garner, 2021). So, what exactly causes the different colors that we see?

The high-energy electrons from the solar plasma transfer their energy onto the oxygen and nitrogen molecules in our ionosphere, exciting their electrons up to higher energy levels. When the electrons calm down and return to their ground state, they emit photons of different colors. The common green hues of auroras are produced by the excitation of atomic oxygen 60 to 120 miles in altitude. (Helmenstine, 2020). Recently, rare pink auroras flooded Norwegian skies for a few minutes on November 3, 2022, as seen in Figure 2.

Figure 2

Pink Auroras over Norway

Image Credit: Markus Varik/Greenlander

An influx of solar wind resulted in a minor geomagnetic storm, creating a separation in Earth's magnetic field. This allowed the solar particles to penetrate deeper into the ionosphere where they interacted with the molecular nitrogen in the lower atmosphere, producing these pink hues. A curtain of light surrounds the poles in an oval shape, plainly named the auroral oval, and varies in size and intensity depending on solar activity. Let us take a closer look at the mechanisms involved in leading toward and within these ovals.

Our magnetosphere is composed of various types of currents and energy flows. One of these is called the field-aligned currents, and they follow Earth's magnetic field lines and connect the magnetosphere to the ionosphere. Norwegian scientist Kristian Birkeland theorized the existence of these currents during his expeditions to the arctic to examine auroras in the early 1900s. He published his findings in his book, *The Norwegian Aurora Polaris Expedition 1902 – 1903*, illustrated in Figure 3.

Figure 3

Birkeland Currents

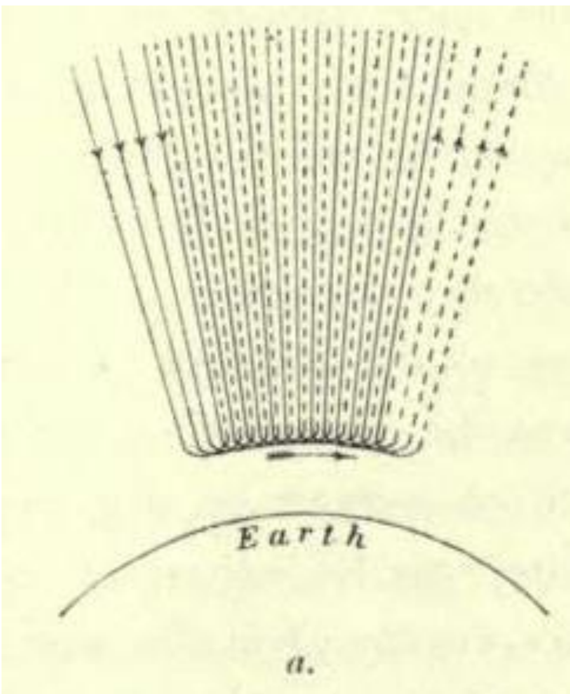

Image Credit: K. Birkeland, p. 105

Studies on the motions of positive and negative charges have shown that positives spiral upwards along magnetic field lines and negatives spiral downwards in the opposite direction. This is known as cyclotron motion, and the negative charges rush into the currents surrounding the poles.

The accelerated electrons flow down along the field lines and end up in another current called the auroral electrojets (AE) located in our ionosphere (Figure 4).

Figure 4

Auroral Electrojet

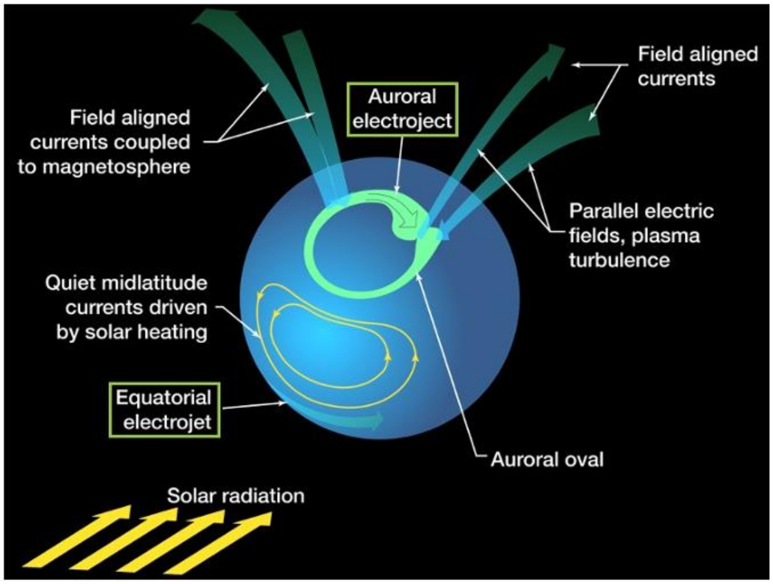

Image Credit: Yee, Gjerloev, Perez, & Swartz

These horizontal jets have two currents flowing in opposite directions, east- and westward. The total current of the AE equals about one million amps (Moldwin, 2008), and scientists use the AE index to determine their strength during geomagnetic storms. Here is where we have the auroral oval! Additionally, the oval expands toward the equator during a solar storm. This expansion is due to the increased number of particles, which increases the AE and electric field strength of the ionosphere. All this intense energy cannot be contained to just the polar regions, so it spreads equatorward and gives people at lower latitudes a treat for the eyes. During geomagnetic storms, auroras can be categorized based on their appearance and where they occur relative to the auroral oval.

Auroras are classified into dunes, arcs, bands, pillars, diffuse, and corona. Arcs are the most common type seen and can transform into bands during high activity. Coronas are rare and only occur during intense solar storms. Auroras that appear outside the oval are known as localized auroras, and there are many different types, as noted in Figure 5.

Figure 5

Localized Auroras

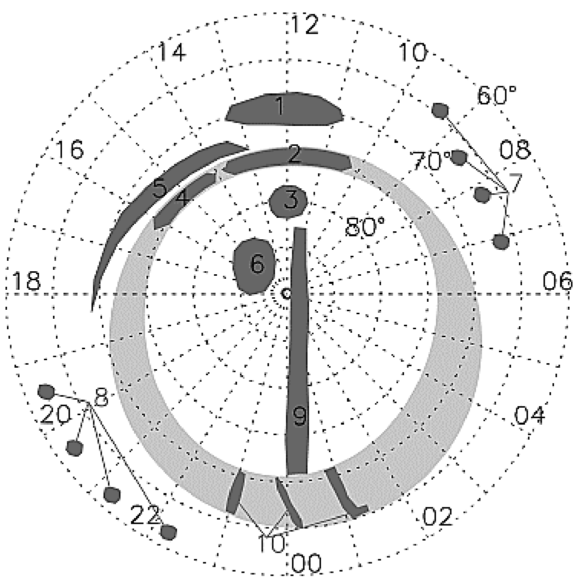

Image Credit: Holzworth and Meng

From a top-down viewpoint, the list is as follows:

1. Midday Subauroral Patches, Dayside Detached Aurora, and Subauroral Proton Flashes
2. South IMF Cusp
3. North IMF Cusp
4. 1500 Magnetic Local Time Spot
5. Afternoon Detached Arc
6. High-Latitude Dayside Aurora (HiLDA)

7. Subauroral Morning Proton Spots
8. Evening Corotating Patches (ECP)
9. Polar Cap Arcs
10. Auroral Streamer

Sometimes a solar wind shock, or jump in pressure, will produce detached auroras, like for number 1. Other times, ions in the plasmasphere become refilled by the ring current and lead to spotty auroras during early morning hours, as in number 7. Further research is in the works to gain a complete understanding of what exactly is happening during auroral events.

The Electrojet Zeeman Imaging Explorer (EZIE) is a NASA-funded mission planned to launch in June 2024. During its operational period of a year and a half, it will study the AE using three CubeSats with a polar orbit averaging around 500 km in altitude. Lead scientists for the project Yee, Gjerloev, Perez, and Swartz (2021) state, “The EZIE constellation will provide, for the first time, measurements with the spatial and temporal resolution required to distinguish between proposed hypotheses for the physical mechanisms behind the auroral and equatorial electrojets.” To achieve this, it will take images and collect magnetic data to track the overall evolution of the jets on a global scale through the Zeeman splitting of oxygen. Scientists hope to gain an in-depth understanding of our AE and apply that knowledge to auroral mechanisms on other planets, like Jupiter and Saturn.

We have only scratched the surface of what auroras have to offer. Their beginnings at the Sun to where they end up in our atmosphere through magnetic reconnection, the Birkeland Currents, and the auroral electrojets display a complicated process. We have also learned that there are several types of auroras, and they do not have to be confined to the oval. Future missions aim to solve decades-long mysteries that have scientists questioning the specifics of auroras. This is certainly an exciting field with lots of potential.

References

Baker, H. (2022). *Solar Storm Smashes Hole in Earth's Magnetosphere, Triggering Extremely Rare Pink Auroras*. Live Science. https://www.livescience.com/pink-auroras-solar-storm

Birkeland, K. (1908). *The Norwegian Aurora Polaris Expedition, 1902-1903*. Christiania H. Aschelhoug & Co.

Frey. (2007). Localized Aurora Beyond the Auroral Oval. *Reviews of Geophysics (1985)*, *45*(1). https://doi.org/10.1029/2005RG000174

Fuller, M. (2020). *There's a New Type of Aurora to Look for on Your Next Northern Lights Tri*p. AFAR. https://www.afar.com/magazine/what-are-the-northern-lights-and-what-do-they-look-like

Garner, R. (2021). *Magnetospheric Multiscale*. NASA. https://www.nasa.gov/mission_pages/mms/overview/index.html

Hatfield, M. (2022). *In Cold Polar Skies, NASA Rocket Will Watch Aurora Turn Up the Heat*. NASA. https://www.nasa.gov/feature/goddard/2022/sun/in-cold-polar-skies-nasa-rocket-will-watch-aurora-turn-up-the-heat

Helmenstine, Anne Marie, Ph.D. (2020, August 28). *What Causes the Aurora Borealis' Colors?*. ThoughCo. https://www.thoughtco.com/causes-aurora-borealcolors-607595

Moldwin, M. (2008). *An Introduction to Space Weather*. Cambridge University Press.

Nakamura, M., Yoneda, A., Oda, M. et al. (2015). Statistical analysis of extreme auroral electrojet indices. *Earth Planet Sp 67*, 153. https://doi.org/10.1186/s40623-015-0321-0

NASA's Scientific Visualization Studio. (2015). *Plasma Zoo: Field-Aligned Current (Birkeland Current).* NASA. https://svs.gsfc.nasa.gov/4264

Petersen, L. (2020). *What Causes the Aurora*. Lee Petersen. https://www.lwpetersen.com/science/what-causes-the-aurora/

Yee, J. H., Gjerloev, J., Perez, R., & Swartz, W. H. (2021). *The EZIE Way to Measure the Ionospheric Electrojets with a Three-CubeSat Constellation*. 35th Annual Small Satellite Conference. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5051&context=smallsat