# Morphology of Auroral Types and Related Phenomena

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# Abstract

The Northern Lights, the Aurora Borealis (or Australis): everyone's seen photos of them, the mysterious, ephemeral celestial phenomena of the poleward regions of the globe. Of interest to both tourists and scientists, the aurora has been extensively studied, but despite decades of research, there is still much to learn about the mechanisms of aurorae and related phenomena. Study of the aurora is important, as it is one of the only ways to see and quantify the invisible mechanics of Earth's magnetosphere, the bubble of magnetism surrounding Earth associated with the Earth's magnetic field as it interacts with the solar wind emitted by the sun. The aurora can take many forms, varying with the conditions of the solar wind and other -as of yet unknown- factors. They are classed into a number of types, which vary from common to rare, from easy to observe to that which requires specialized equipment. This paper will give an overview of all the types of aurorae that I found in my research, beginning with a brief overview of the three standard types and focusing on the rarer, less well-known varieties, including related geomagnetic phenomena that are not technically defined as "aurora." Some evidence has been found for connections between some of these lesser-known aurorae to a degree that is not fully understood. Although these types have been studied to greater or lesser extent, it is concluded that more research is needed in the new topic of auroral interconnectivity.

# Background Information

To understand the mechanics of the many and varied auroral types that are the focus of this review, it is necessary to first go over how they form, tracing their origins back to the sun. This will be a very brief overview covering the major mechanics of space weather. In order to keep the section to a reasonable length many of the highly complex dynamics of the sun and solar wind have been greatly oversimplified. Bear in mind this is not a comprehensive explanation, as there is much here that is still not fully understood by science. This is the root cause of many of the uncertainties inherent in our understanding and prediction of the aurora.

## Sunspots and the Solar Cycle

The sun has a magnetic field, similar to the Earth, but because the sun is not a solid body, as different latitudes move at different speeds its magnetic field becomes highly contorted. Sunspots are areas of the sun that appear as dark patches on the sun's surface (photosphere), dark because they are cooler than the surrounding sun. Here, strong magnetic fields emerge from the interior of the sun and form tight groupings of magnetic field lines and loops. Driven by mechanics in the interior of the sun that are not fully understood, these sunspots grow and fade, and can be simple or complex.

## Sunspot Complexity and Configurations

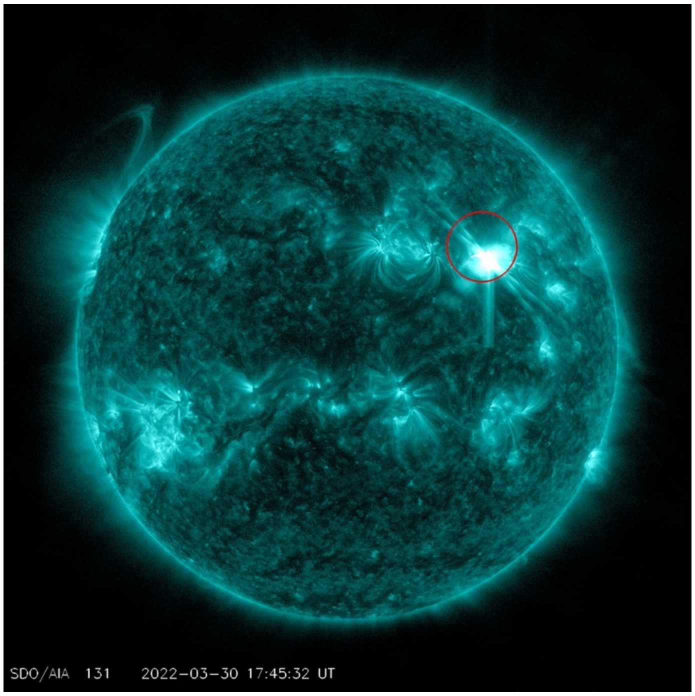
Depending on the magnetic configuration of the sunspot, i.e., the distribution of areas of positive and negative polarities or magnetic field lines going "into" or "out of" the sun, an Active Region (AR) can be simple or complex, roughly equating to how intermixed and compressed areas of different polarities are. When an AR is simple, the magnetic loops are stable. When an AR is complex, the magnetic field lines can become unstable, and occasionally they will "snap" and undergo magnetic reconnection, an explosive event that is known as a solar flare.

## Solar Flares

Solar flares, the explosive magnetic reconnection events typically driven by complex sunspot groups, are the main source of "space weather". The flares emit radiation from the x-ray to UV wavelengths (and rarely visible light), and are measured by the x-ray flux received by GOES satellites. Flares are classed as A, B, C, M and X-classes, with each class being subdivided 1 through 9, i.e., C2, M5. 10 becomes the next letter class, except for the X class which can exceed 10, i.e., X12. The higher the classification the stronger the flare, and the higher the potential for substantial or noticeable space weather. One of the principal ways flares do so is by launching coronal mass ejections.

**Figure 1**

*X-class solar flare*



*Note.* A strong X1.3 solar flare, visible as the bright circled region. Image in the ultraviolet band, taken by Solar Dynamics Observatory. Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams. The red circle highlighting the solar flare was added.

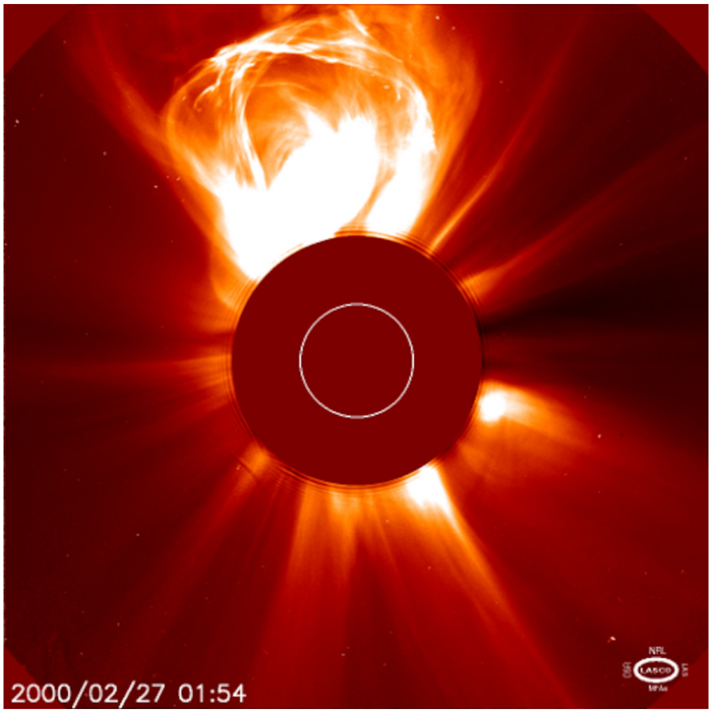
## The Solar Wind and HSSs/CMEs

Coronal mass ejections, or CMEs, are the most noticeable kinds of space weather. The sun emits a constant stream of charged particles known as the solar wind. This stream is typically relatively slow and weak, but coronal mass ejections take the form of strong solar wind enhancements, large “puffs” or gusts of the solar wind. As the name implies, they are considerable masses of the sun’s atmosphere (corona) that are launched out into space, typically by the energy released in solar flares. These clouds of charged particles move faster than the ambient solar wind, are much denser with more charged particles, and contain stronger magnetic fields, known as the IMF, or Interplanetary Magnetic Field. When CMEs arrive at Earth and interact with Earth’s magnetic field, known as the magnetosphere, powerful aurorae can occur.

High Speed Streams (HSS) of solar wind are the second leading cause of heightened auroral displays, producing strong aurorae in the upper latitudes, and occasionally bringing visibility to the middle latitudes. Exactly as the name describes, they are a stream of solar wind that is flowing much faster than the ambient wind, as fast as many minor to moderate CMEs. Whereas a CME is like a fast “puff” of wind, the HSS takes the form of a steady stream that can last up to several days. A typical HSS contains weaker IMFs than a CME, so they typically produce less vivid or equatorward displays than strong CMEs, although they can be comparable to minor or moderate ones. High speed streams are formed by Coronal Holes (CH) on the Sun, areas where the outer layer of the Sun’s atmosphere, the corona, is absent, allowing faster solar winds to flow into space. When a hole forms and is positioned properly, Earth receives the HSS a few days after the hole faces Earth, with the duration and strength of the HSS broadly relating to the size and positioning of the hole.

**Figure 2**

*A strong CME*



*Note.* A strong CME is seen leaving the sun, imaged by the Large Angle and Spectrometric COronagraph (LASCO) instrument on the Solar and Heliospheric Observatory (SOHO) spacecraft. Credit: ESA & NASA/SOHO

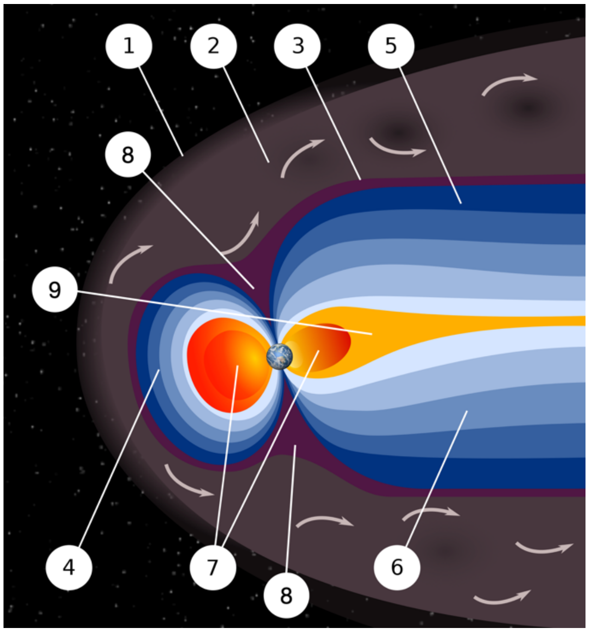
### How Space Weather Produces Aurorae

As discussed above, the solar wind consists of charged particles and magnetic fields emitted by the sun. When these arrive at Earth, they meet Earth's magnetic field, the magnetosphere. Because the particles are electromagnetically charged, when they enter Earth's magnetic field, they feel an electromagnetic force. The shape of Earth's magnetic field, like a bar magnet, has magnetic field lines that enter and exit the Earth at the poles and loop from one pole to the other. Most of the solar wind is deflected off the magnetic field, which saves humans from any ill effects of the radiation, and prevents our atmosphere from being eroded. However, near the poles where the field lines are directed into and out of the planet rather than roughly parallel with the surface as is the case in lower latitudes, the charged particles of the solar wind can be funneled down into the upper atmosphere. This is why aurorae are primarily seen at high latitudes, although heightened solar wind can cause the magnetic field to become more compressed, and the aurora to move towards lower latitudes. The auroral zone is called the auroral oval, a ring-shaped region around the poles.

When the charged particles enter the upper atmosphere, they may collide with atoms in the atmosphere and cause them to glow by ionizing them. The different elements in the atmosphere (primarily oxygen and nitrogen) glow in different colors at different altitudes when ionized, giving the variety of colors exhibited by aurora. Structures within the magnetosphere mold the flows of charged particles, and thus the ionization is shaped into the multi-formed aurora. In general, stronger solar winds and IMFs produce stronger, brighter, and faster-moving aurora, but within this generalization lies many unique forms.

**Figure 3**

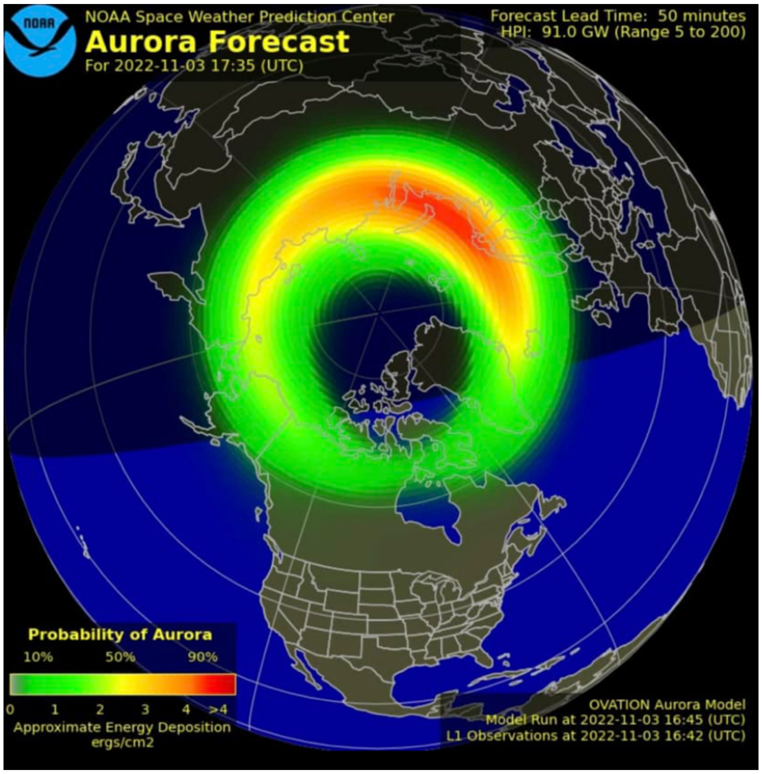
*Earth's magnetosphere*



*Note.* This is an artist's depiction of the structure of Earth's magnetosphere. It is not necessary to memorize all of these, but it may be helpful to refer back to it as these terms are mentioned in the following sections. 1) Bow shock. 2) Magnetosheath. 3) Magnetopause. 4) Magnetosphere. 5) Northern tail lobe. 6) Southern tail lobe. 7) Plasmasphere. 8) Polar cusps. 9) Plasma sheet. Original image by NASA, used with permission. Edited to add polar cusps and plasma sheet.

**Figure 4**

*Auroral oval*



*Note.* The auroral oval forms a doughnut-shaped region around the poles, broadening, moving equatorward, and stretching further around the dayside when the geomagnetic activity increases. This image is from a period of heightened activity, during the day for North America. Green, yellow, orange, and red represent heightened probabilities to see the aurora, in that order of likelihood. A near-mirror image oval exists in the southern hemisphere surrounding the south magnetic pole. Image by NOAA Space Weather Prediction Center.

# Standard Aurora: Morphology and Mechanics

A highly dynamic and variable phenomenon, the aurora can take a multitude of forms, from those familiar to unfamiliar, and from common to rare. Due to this large degree of variety, other processes that can cause light emissions in the atmosphere are sometimes incorrectly attributed to be new kinds of aurora, until they are more fully understood. Studying the many forms of the aurora is of interest to scientists, as they can provide insight into the working of Earth's magnetosphere, a region still not fully understood. The light emissions from aurorae and related phenomena can give a visual glimpse into mechanics that would otherwise be invisible and difficult to detect, such as gravity waves in the atmosphere or magnetic field lines and boundaries.

Most aurora that are visible to the naked eye appear as one or more of the three common forms: auroral arcs, bands, and rays. These are the classic aurorae, those most easily seen and photographed, what most people think of when they hear "northern lights." Due to their commonality and ease of observation, much more is known about these types than some of the other, more elusive varieties. This review will focus on highlighting the less studied types, beginning with an overview of the basic forms, as that knowledge will be helpful in contextualizing some of the more obscure morphologies.

## Auroral Arcs

The most stable form of aurora, these take the shape of a glowing arc that spans the sky in a gentle curve from east to west. Arcs are typically brighter in the middle and fade out near the top and bottom, but lack distinct boundaries. Auroral arcs are almost always green, the most common aurora color. Although the most stable of the auroral forms, it does exhibit movement, sometimes growing or reducing in size and brightness, and moving equator- or pole-ward.

Auroral arcs are typically associated with periods of relatively low auroral activity, or the period before a geomagnetic storm or substorm (a localized outburst of aurora) when the aurora is gaining strength. During this time, the arc will widen, brighten, and move equator-ward. If it gains enough strength, it will usually break up into the other two common forms of aurorae.

**Figure 5**

*Auroral arc*

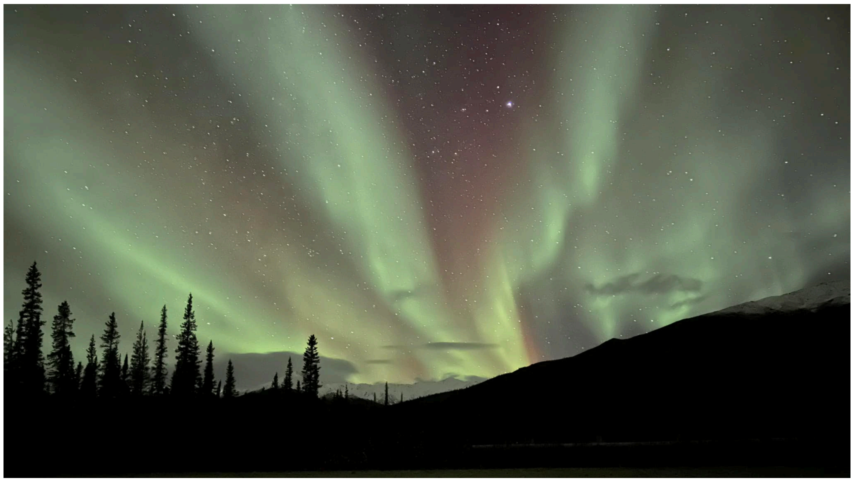
*Note.* An auroral arc is seen in this image, a single, stable, east-west band of emission. Photo by Melissa F. Kaelin, used with permission.

### Auroral Bands

This is the classic "northern lights", or the form of the aurora that is often described as "ribbons of light." Sometimes also called curtains by aurora watchers, these take the form of a relatively small (as compared to an auroral arc) bands of light with more distinct edges, that often curve back and forth as they cross the sky. Bands often exhibit more and faster motion (as compared to an auroral arc), especially at higher latitudes or stronger geomagnetic activity (storms). Bands can appear as individuals or multiples, typically stretching primarily from east to west, but with stronger activity they can become increasingly twisted and contorted, running in all directions. When seen from high latitudes where the aurora is overhead, the bands appear as narrower ribbons of light. When seen from lower latitudes, where the aurora is viewed far away in the northern sky, the side view causes the bands to appear more as curtains of light, with a sharper, brighter lower edge, and a top that gradually fades away. Bands are most commonly green, with pinks or reds appearing during stronger activity, or very rarely, as blues or purples.

**Figure 6**

*Auroral bands*



*Note.* Several auroral bands snake across the sky. Photo by Melissa F. Kaelin, used with permission.

### Auroral Rays

The most dramatic of the basic aurora types, rays (often called pillars by aurora watchers) are typically the form of basic aurora associated with the strongest activity, such as geomagnetic storms or local substorms. This form of aurora appears as one or more pillars of light stretching vertically through the sky, and is often associated with other forms, such as bands. Rays are one of the most dynamic forms of aurora, with their size, brightness, and position changing rapidly, over a span of tens of seconds or even less. Their color can be constant, or change from top to bottom with altitude. Rays are often considered to be one of the most visually spectacular forms, especially when seen as a “corona”.

Auroral “coronas” are often treated as a separate form of aurora by casual aurora watchers and photographers, as indeed they appear visually different from any other form. However, in actuality, the corona is merely a display of auroral rays where the rays happen to originate from a point directly above the observer’s position. This causes the rays to appear to fan out radially across the sky from the zenith directly over the observer, creating the starburst pattern of a corona. Due to this requirement of being observed from directly under the auroral oval, this is a form (or more accurately, a viewpoint of rays) that is typically only seen from very high latitudes, although strong to extreme geomagnetic storming can cause this to be visible at lower latitudes. As the corona is just a different perspective on auroral rays, it shares their characteristics of bright colors and fast, dynamic movement.

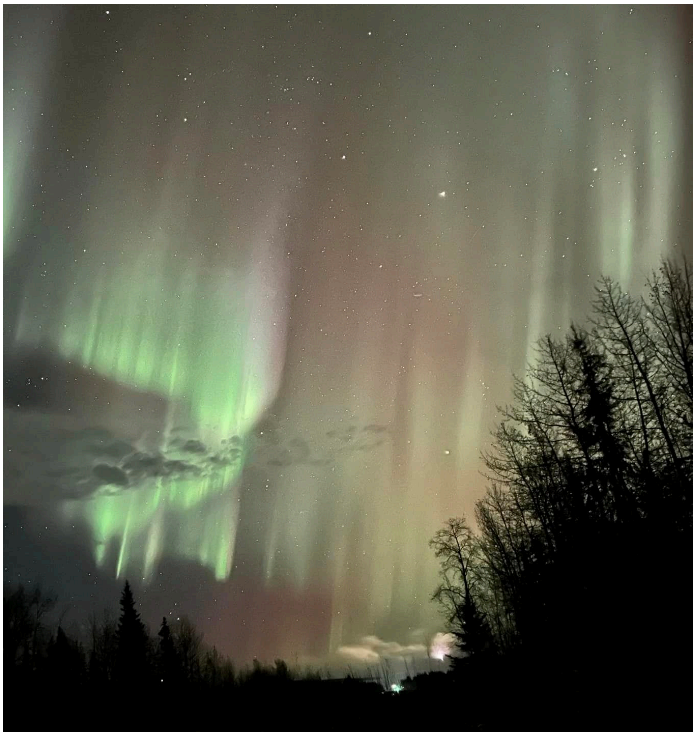
**Figure 7**

*Auroral rays*

*Note.* In this image several rays are seen, forming the vertical pillars of light, originating in a green arc. Photo by Samuel L Warfel.

**Figure 8**

*Auroral rays cont.*



*Note.* In this image, a profusion of auroral rays is seen, along with a band. Photo by Melissa F. Kaelin, used with permission.

**Figure 9**

*Auroral corona*

*Note.* This image shows an auroral corona, the starburst-like form when rays originate from above the viewer, and appear to fan out radially across the sky. Photo by Dixie J. Burbank of Cosmic Chaos Adventures LLC, used with permission.

## Lesser Known Aurorae and Related Phenomena: Morphology and Mechanics

The above three forms of aurorae make up the bulk of that which is easily visible to the casual observer. But as stated previously, the aurora has a large diversity of forms with wide-ranging appearances, mechanics, and impacts. Some are common but largely invisible to the human eye, others are quite rare, some are both or some combination thereof. The three common types are often referred to as *discrete aurorae*, referring to their brightness and distinct shapes. The lesser known types of aurorae are the main focus of this review, which will cover the following types: diffuse aurora and subtypes, proton aurora, STEVE and picket fence aurora, SAR arcs, polar cap aurora, polar cusp aurora, and dunes aurora. These aurorae and related phenomena are beautiful in their own way, as well as offer insights into the workings of Earth's magnetosphere that cannot be gained by study of the common discrete aurora.

### Diffuse Aurora

The diffuse aurora is the most common of the lesser known types of aurorae. It is found to be present most of the time, however it is usually quite dim, not visible to the eye, and only to cameras and specialized instruments. It brightens substantially during periods of increased auroral activity, such as the appearance of discrete aurora (Lui et al., 1973).

Because of the difficulty of observation and its drab appearance, the diffuse aurora has been understudied. However, Newell et al. (2009) found that it accounts for 84% of the total kinetic energy deposited in the ionosphere during quiet activity, and even during periods of higher activity with active discrete aurora the diffuse aurora still accounts for 71% of the energy.

Therefore, for understanding the mechanics of the magnetosphere, knowledge of the diffuse aurora, the least glamourous of the aurorae, is critical (Newell et al., 2009).

The diffuse aurora typically appears in a belt that is equatorward of the discrete auroral oval. Due to this positional overlap with the proton aurora (covered in the following section), the diffuse aurora was initially ascribed to proton precipitation, but the diffuse aurora consists of the same electron precipitation causing oxygen and nitrogen emissions that is standard to the basic discrete aurora types (Lui & Anger, 1973). The source of these charged particles is Earth's equatorial plasma sheet, a region of hot, dense plasma arranged in a sheet along the equatorial region of Earth's magnetosphere (Ackerson & Frank, 1972). Particles (mainly electrons and some protons) are disturbed from this region and flow polewards and inwards due to wave-particle interactions in the plasma sheet. Zhang et al. (2014) determined that ECH waves (Electron Cyclotron Harmonic waves, which are electrostatic waves that propagate roughly perpendicular to an ambient magnetic field) are responsible for driving the majority of diffuse aurora, although chorus waves, another type, are also involved.

**Figure 10**

*Diffuse aurora*

*Note.* In this image, light from a diffuse aurora illuminates the sky. The darker shapes and patches are clouds, which appear dark by contrast with the light from the diffuse aurora behind them. Photo by Melissa F. Kaelin, used with permission.

### *Pulsating Aurora*

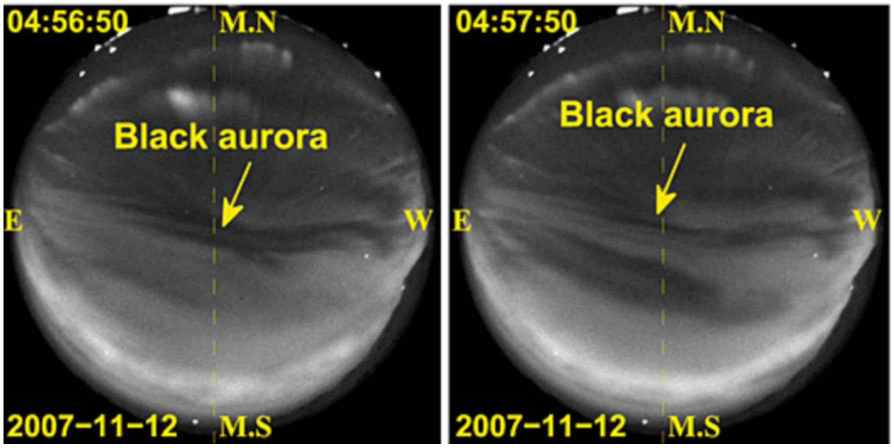
The diffuse aurora is one of the broader categories of aurorae and has several notable sub-types, the most documented of which is pulsating aurora. As described by Nishimura et al. (2019), this subtype appears within a diffuse aurora, and takes the form of patches that blink on and off, over periods of 2-20 seconds. Although dimmer than the discrete aurora, the pulsating aurora can be visible to the human eye, and is predominantly green (Nishimura et al., 2019). The cause of the unique pulsations is intermittent electron precipitation. The electrons come from the equatorial regions of the magnetosphere, where they are disturbed and sent along magnetic field lines into the polar regions by ECH waves and electron chorus waves (Fukizawa et al., 2018; Kasahara et al., 2018). The periodic nature of these waves gives rise to the intermittent electron precipitation, and thus the pulsating aurora. Since this is the same basic process that forms diffuse aurorae, pulsating aurorae are observed within diffuse and considered a subtype thereof.

### *Black Aurora*

The intriguingly named “black aurora” is one of the lesser known auroral types. First discovered and classified by Royrvik and Davis back in 1977, it was defined as a small and distinct region within a background of diffuse and/or pulsating aurora where auroral emission is absent. This gives the impression of “black” aurorae alongside the more conventional type. Of course, true black aurora would be impossible, as ionized gases only emit light and never absorb it, so aurorae, -by definition of light emissions from gases undergoing ionization due to charged particle precipitation- can never be darker than no emissions at all, or simply “no aurora”. Most of the time this is not a cause for interest, as the non-auroral sky is simply the default for most, if not all, of the planet. However, these distinct patches of the absence of auroral emissions within a setting of diffuse aurora are worthy of note as they can provide insight into the structure and mechanics of the diffuse aurora, or aurorae in general (Royrvik and Davis, 1977). Black aurorae are often found in the late recovery phase of an auroral substorm (Trondsen & Cogger, 1997). Trondsen and Cogger (1997) analyzed 50 hours of high-temporal resolution auroral imagery and classified black aurorae into three different types: black objects (consisting of black patches and arc segments), black arcs, and black vortices. They found that black objects only drifted eastward, at odds with the westward drifting features of the midnight sector diffuse aurora in which they were observed.

**Figure 11**

*Black aurora*



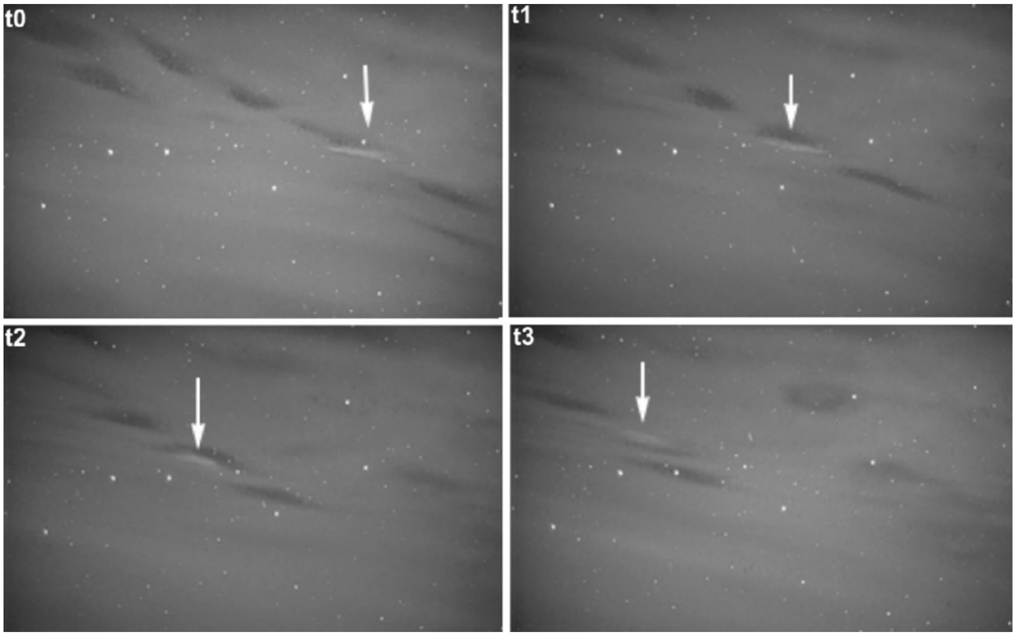
*Note.* In this image, black aurorae are seen in a background of diffuse aurora. Image from “An extensive survey of dayside diffuse aurora based on optical observations at Yellow River Station” (2015) by De-Sheng Han et. al., Journal of Geophysical Research, 120(9). https://doi.org/10.1002/2015JA021699 Used under CC BY-NC-ND 4.0. Image has been cropped to highlight the black aurora.

### ***Anti-Black Aurora***

In 2021 Nel et al. discovered and named a rare auroral phenomenon, the anti-black aurora, which they found to be associated with 10% of black aurorae. This takes the form of a patch of higher luminosity directly alongside the patch of black aurora, brighter than the diffuse background. The patches of anti-black aurora are similar in size and shape to the patches of black aurorae, typically appear alongside them, and move parallel to them in sync with their drift. The anti-black aurora can appear on either side of the black aurora, sometimes switching sides for unknown reasons. This elusive form of aurora is still new enough that published research on it is limited to only Nel et al.'s initial discovery, and the cause behind the anti-black aurora is not yet fully understood (Nel et al., 2021).

**Figure 12**

*Anti-black aurora*



*Note.* An anti-black aurora, seen alongside the black aurora, in a surrounding of diffuse aurora. Image by Dr. Amoré Nel, used with permission.

## Proton Aurora

The definition of “aurora,” as touched on previously, is the glow by ionization of atmospheric gases excited by solar charged particle precipitation. Note that this does not specify the type of charged particle. The solar wind contains several different particles, being made of mostly electrons, protons, and alpha particles. All of the true aurora covered in this study (thus, not including the non-auroral phenomena of the mauve arc STEVE and SAR arcs) are all caused by precipitation of electrons specifically. This raises the logical question: what about the protons? There are indeed proton aurorae, following different mechanics and exhibiting different characteristics than the standard electron aurora. Due to the rarity and variability of proton aurorae, the term has sometimes been applied to phenomena that aren’t proton aurora before their true cause was fully understood. This was the case with STEVE and the electron diffuse aurora.

Gallardo-Lacourt et al. (2021) gave an overview of proton aurorae. They are rare and dim because bare protons cannot emit any photons, but when protons precipitate into the atmosphere they can occasionally collide with gases and become hydrogen atoms, which can then emit photons at certain hydrogen-specific spectral lines. Sometimes this proton aurora appears in the auroral oval along with the discrete and diffuse electron aurora, taking the form of a type of diffuse aurora that can be identified with spectroscopy as resulting from the above hydrogen emissions. These displays are found equatorward of the auroral oval before magnetic midnight, and then after magnetic midnight it shifts and is found poleward of the oval (Gallardo-Lacourt et al., 2021).

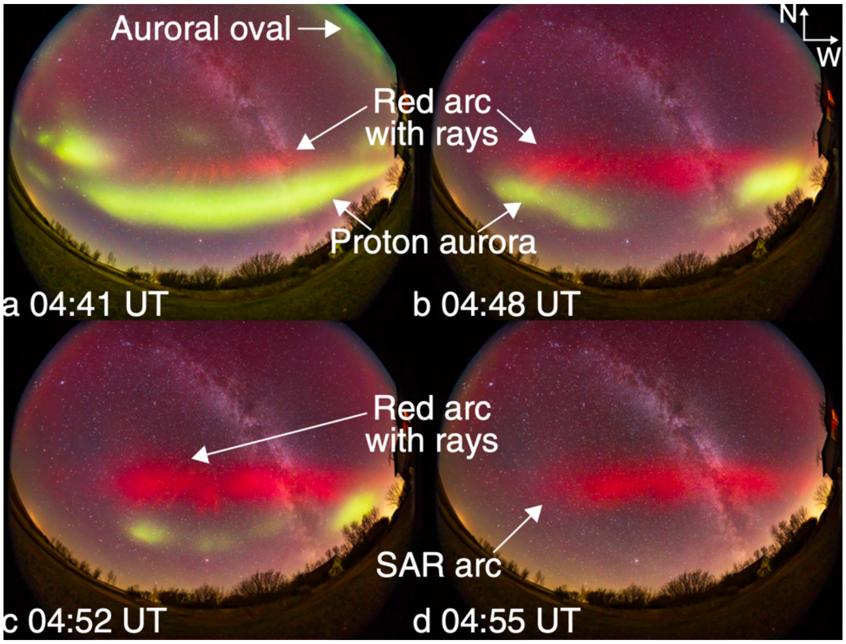
A study by Frey in 2007 described one form of proton aurora found outside the auroral oval in the subauroral region, termed Subauroral Morning Proton Spots, or SAMPS. Taking the form of amorphous blobs, these also emit light through the conversion of protons to hydrogen atoms and emitting a photon. As the name suggests, SAMPs often occur in the subauroral zone outside the auroral oval, the same area as STEVE and SAR arcs. This is indicative of the connection between SAMPs and the plasmapause, the same region where the processes that drive STEVE and SAR arcs occur. SAMPs form in the recovery phase of a geomagnetic storm, and their equatorward extent correlates strongly with the minimum Dst (Disturbance Storm Time, a measure of the strength of geomagnetic storms) index of the preceding storm, with a stronger storm leading to more equatorward SAMPS. They appeared when the Dst had relaxed to 1/5th of its minimum value during the strongest part of the storm. Frey found SAMPs could last for several hours, and did not seem associated with any particular solar wind conditions (Frey, 2007).

Proton aurorae do not follow the same rules as electron aurorae in terms of formation and intensity. A study by Laundal and Østgaard (2008) showed that intense proton aurorae are strongly correlated with high solar wind dynamic pressure, and not just with a southward IMF (interplanetary magnetic field), as would be the case for normal electron aurorae. This was determined by studying several events with high dynamic pressure and observed proton aurorae that occurred during low geomagnetic (discrete aurora) activity due to a northward directed IMF. Also examined was one event that contained both a southward IMF and high dynamic pressure, and this combination produced a particularly intense global proton aurora (Laundal and Østgaard, 2008).

Nishimura et al. (2022) found that there may be connections between proton aurorae and SAR arcs, a form of non-auroral atmospheric phenomenona related to geomagnetic storming, which was previously not thought to be related to any type of aurora. Citizen scientist photographs showed the proton aurorae appearing before and transitioning to a SAR arc, even though SARs arc themselves are not believed to be powered by proton precipitation. The proton aurora observed take the form of diffuse but localized green blobs and arc segments, which may be SAMPs ((Frey, 2007; Nishimura et al., 2022). This possible connection between proton aurorae and SAR arcs illustrates how (especially with the lesser-seen proton aurora), there is still much left to learn about the workings of our magnetosphere.

**Figure 13**

*Proton aurora*



*Note.* In this image from “Interaction Between Proton Aurora and Stable Auroral Red Arcs Unveiled by Citizen Scientist Photographs” (2022) by Nishumura et al., the proton aurora is seen as the green blobs, together with a SAR arc. Used with permission.

## STEVE

STEVE, or “Strong Thermal Emission Velocity Enhancement”, is a relatively recently described type of aurorae and related phenomena. STEVE has been known and documented by aurora photographers for decades, but it was not until the twenty-tens that it came to the attention of the geomagnetism science community. This elusive apparition had been nick-named “Steve” by the aurora photographers, and was given the backronym “STEVE” (Strong Thermal Emission Velocity Enhancement) to carry on the original name (Gallardo-Lacourt et al., 2018).

STEVE has two main forms. One is the classic STEVE, consisting of a mauve, whitish or pinkish arc, forming a narrow and distinct band from east to west, typically from horizon to horizon. The other is a green form, similar to many aurorae but appearing as a series of evenly spaced rays or patches. This form is termed the “picket fence” due to its resemblance to evenly spaced pickets (MacDonald et al., 2018). The picket fence is usually seen in association with the mauve arc, where it typically appears alongside it (Nishimura et al., 2019). The picket fence may appear for a shorter period than the mauve arc, and not all mauve arcs will include a picket fence (Nishimura et al., 2019). Both appear well south of the auroral oval at that time and are typically associated with enhanced geomagnetic activity, such as geomagnetic storming (Gallardo-Lacourt et al., 2018)

While they are strongly associated with aurorae, are STEVE (mauve arc and picket fence) actually aurorae themselves? The answer is no and yes. Gallardo-Lacourt et al. (2018) correlated an observed STEVE event with data from the POES-17 satellite and found no particle perception during the event in that area. The definition of “aurora”, across all its many forms, is light emissions from ionization of gas in the atmosphere caused by charged particles precipitating into the atmosphere from the solar wind. Since this observation of STEVE was found to lack particle precipitation, it can be determined that that is not the cause of the mauve arc STEVE. While strongly associated with auroral events, and a mechanism of the magnetosphere, the mauve arc STEVE is not an aurora itself. Note that this is specific to only the mauve arc, not the green picket fence. The event analyzed by Gallardo-Lacourt et al. (2018) did not feature a picket fence, so we must look to later studies to determine its cause.

Nishimura et al. published a study in 2019 again correlating ground imagery with satellite data for several events, this time including one where the picket fence appeared. They observed particle (electron) perception was present for the event where the picket fence was observed, and was absent when only the mauve arc was seen. This led them to conclude that the picket fence is driven by said particle perception, making it an aurora, even though it appears separate from other aurorae, well equator-ward of the auroral oval, and in conjunction with the non-aurora mauve arc STEVE. This is not entirely surprising, given the green coloration and dynamic behavior of the picket fence, which is very similar to other aurora. This suggested it was more likely to be an aurora itself than the mauve arc, a color that is not associated with any auroral emissions. The source of the particles that drive the picket fence aurora is sufficiently far from Earth to send particles evenly into both hemispheres, as the picket fence has been observed simultaneously in both hemispheres, making it a hemispheric conjugate phenomenon. Although an aurora, the picket fence is controlled by a quite different mechanism than the other forms of aurorae. When the earthward boundary of the plasma sheet is disturbed by broadband waves, additional electrons are ejected from the plasma sheet and sent into the atmosphere, causing the picket fence aurora (Nishimura, et al., 2019).

If the mauve arc, the "classic" STEVE, is not an aurora (driven by particle perception), then what causes it? Nishimura et al., (2019) found that STEVE is associated with fast plasma flows and sharp plasma boundaries in the ionosphere. These fast and dense streams of plasma, like a "river" of charged particles, become heated due to friction and emit the light that is observed as the mauve arc STEVE. This occurs in the plasmapause, the boundary region between the plasma that precipitates into the auroral oval, and the plasmasphere, the region that does not precipitate. This explains why STEVE is typically seen well equator-ward of the auroral oval. Unlike the picket fence, the mauve arc has not been observed as a conjugate phenomenon, likely owing to its more localized formation in the ionosphere, as opposed to the picket fence being driven from far out in the plasma sheet (Nishimura et al., 2019).

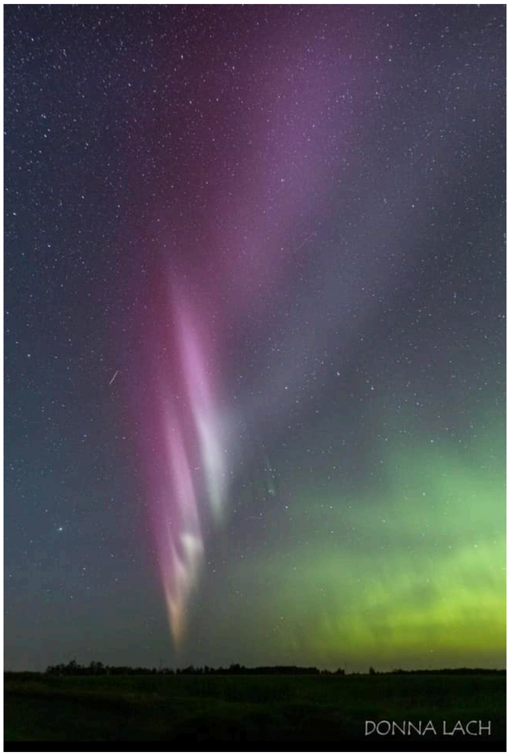
**Figure 14**

*STEVE with a picket fence*

*Note.* Here a strong mauve arc STEVE is seen together with a green picket fence. They form a band running east-west from horizon to horizon. This image looks north-west. The bright green aurora to the lower right is the normal discrete auroral oval, with STEVE appearing separate and equatorward. Photo by Donna Lach, used with permission.

**Figure 15**

*STEVE without picket fence*



*Note.* Here STEVE appears without the companion picket fence, during the same storm as the above figure showing both, illustrating that the picket fence can appear and disappear during the same STEVE event. Photo by Donna Lach, used with permission.

## SAR Arcs

SAR Arcs, or Stable Auroral Red Arcs, have been known to science for a long time, but are still not fully understood, with new discoveries being made that force revision of our existing theories. As described by Nagy et al. in 1970, SAR arcs appear as a band of light emission at only the 6300 Å wavelength, one of the reddest phenomena in the sky. The band extends from the east horizon to west, is several magnetic degrees wide, and remains somewhat constant in brightness and position throughout the night, leading to the "stable" in the name. The arcs are usually observed in mid-latitudes, well equatorward of the auroral oval (Nagy et al., 1970). In fact, SAR arcs occur in the plasmapause, the area just outside the plasmasphere, detailed in the previous section on STEVE, which forms in the same region. Although typically described as forming within the recovery phase of substorms, they have been found to begin in the main phase onset (Mendillo et. al., 2016), suggesting the theory may need revision.

SAR arcs were named as such before the mechanism behind them was known. Because SAR arcs appear similar to aurorae, and their appearance and intensity is correlated with heightened geomagnetic and auroral activity, i.e., geomagnetic storming, terming it an aurora seemed logical. However, this is not accurate. SAR arcs are caused by heat energy leaking out of Earth's ring current system, not direct charged particle precipitation (Rees & Roble, 1975). Earth's ring current is an electrical current that encircles Earth, carried by charged ions, and is a component of the magnetosphere. The ring current is always present, but during geomagnetic storms additional energy is deposited in it, and it strengthens and moves deeper into the magnetosphere. This leads to some of the heat reaching oxygen molecules with sufficient energy to heat them to the point of excitation to emit light at 6300 Å (Angstroms, a red wavelength) (Rees & Roble, 1975).

As SAR arcs are driven by the ring current, and the strength of the ring current is given by the Dst index, a strong correlation is observed between the Dst strength and SAR arc visibility (Rees & Akasofu, 1963). This broadly shows the connection between strong geomagnetic storming, indicated by a more negative (stronger) measurement of the Dst, and SAR arcs (Rees & Akasofu, 1962). Nagy et. al. (1970) also observed a correlation between SAR arc visibility and the KP index, another measurement of geomagnetic activity, but one based on ground magnetometers, rather than the ring current out in the magnetosphere, as is the case for the Dst index. However, due to the relative temporal stability of the ring current, Dst, and SAR arcs as compared to the highly variable KP index, the Dst index tracks the strength and visibility of SAR arcs much more closely than does the KP index (Nagy et al., 1970).

As discussed above in the section on proton aurora, there is some evidence that although the SAR arcs themselves are not powered by particle precipitation, they may be initiated by protons. A recent study by Nishimura et al. in 2022 examined photographs by citizen scientists that show red and green blobs that then transition to a SAR arc. The green diffuse emissions were identified as proton aurorae (and the associated red emissions with secondary electron precipitation) using satellites that passed overhead. A repeatable sequence was observed in three events, suggesting SAR arcs can be initiated by secondary electrons associated with proton aurorae. This does not contradict the theory that the main energy source for SAR arcs is heat energy from the ring current, but it does expand on it (Nishimura et al., 2022). A newer study, this calls for more research, likely again leveraging citizen science photographs.

Although the “Stable Red” of the name is generally accurate, more recent studies have revealed variability in both of these aspects. Together with the inaccuracy of terming it an “aurora,” this may well be the worst-named geomagnetic phenomena. Although SAR arcs often exhibit fairly stable behavior, a study by Mendillo et al. (2015) analyzing an extensive twenty-five years of imagery containing 314 SAR arcs found that a substantial amount of variability was displayed, contradicting the “stable” of the name. They found multiple SAR arcs at the same time in the camera’s field of view, which sometimes merged and split over short timescales. They also observed variation in forms similar to that of a discrete aurora: billows, curls, rays, fingers pointing north or south, etc. (Mendillo et al., 2015). This wealth of variation calls into question our current theories of the formation of SAR arcs and opens the door for more research, possibly linking some of the more unusual SAR arc events with satellite data from the magnetosphere.

As to the "Red", SAR arcs are defined by emission only at the oxygen line of 6300 Å. A study by Mendillo et al. (2016) has found rare events that departed from spectral purity, including some emissions in oxygen's other spectral line of 5577 Å. The emissions are faint, but when viewed in context of the simultaneous emissions at 6300 Å, the connection is obvious. Due to their rarity and appearance of discontinuous patches, the authors do not suggest this as a theoretical "SAG", Stable Auroral Green arc, but rather multiple emission lines within a SAR arc. However, even this is sufficient to call for investigation into how it formed, as the usual theory for the formation of SAR arcs relies on energy drainage from the ring current via electrons that are able to cause emissions at 6300 Å, but not 5577 Å. Candidates for a cause include ion precipitation, such as $H^+$ ions, and low-energy electron precipitation from the plasma sheet (Mendillo et al., 2016). If this is the case, then perhaps the original naming of "Auroral" was less inaccurate then has since been presumed, even as the "Red" is shown to be incomplete.

**Figure 16**

*Sar arcs*

*Note.* In these two panoramas a SAR arc is seen, the faint red band arching across the sky. The glow from the discrete auroral oval is seen in the background, and the second image features a likely proton aurora between the auroral oval and SAR arc. Photos by Michele Sadauskas, used with permission.

## Polar Cap Aurora

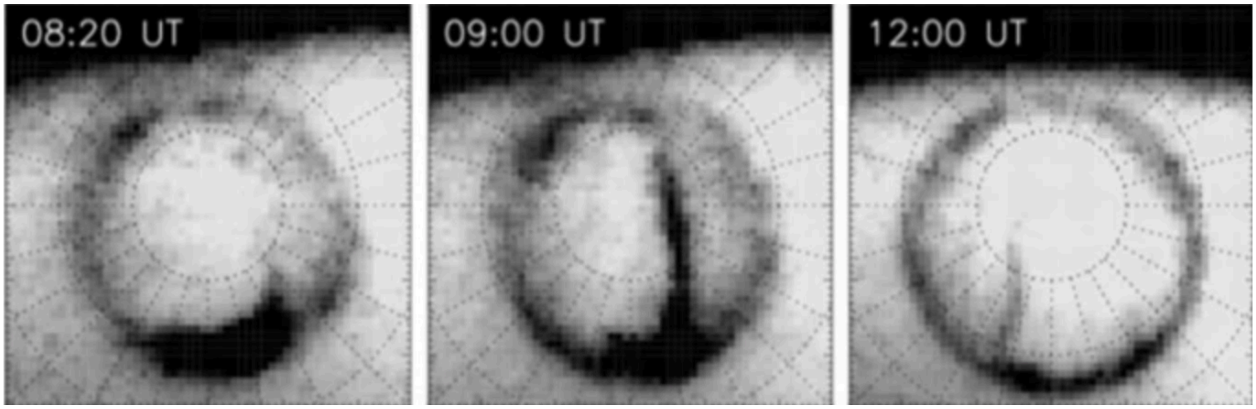
The majority of aurorae form in the “auroral oval,” the doughnut-shaped region surrounding the poles, or the subauroral zone, equator-ward of the auroral oval. This leaves a “hole” centered on the poles where typical aurorae are not found. However, there are some rarer types that have been observed in this region, called the polar cap.

The most documented form of polar cap aurora is the “transpolar arc,” an overview of which is given by Hosokawa et al. (2020). Transpolar arcs take the form of an auroral arc spanning the polar region aligned with the sun, connecting local magnetic noon and midnight in the auroral oval directly across the polar cap. When the transpolar arc spans directly across the polar cap in a straight line, it is sometimes called “theta aurora” for the shape of the auroral oval plus the transpolar arc. Due to how they frequently form at local magnetic noon and follow magnetic lines of longitude, (trans)polar arcs are also sometimes called “sun-aligned arcs.” These arcs often move and curl across the polar regions, forming and remaining on the dawn- or dusk-side of the auroral ovals. Only sometimes do they strengthen and span directly across the poles, forming a true theta aurora (Hosokawa et al., 2020). On rarer occasions, the polar cap may be filled with multiple arcs, forming what has been termed a “double theta,” exhibiting more dynamic properties than typically associated with polar cap/theta aurorae (Newell et al., 1999). Interestingly, it has been documented that these theta aurorae or transpolar arcs only occur during northward-directed IMFs, in what would be generally described as “quiet” auroral or geomagnetic conditions (Ismail et al., 1977).

As these are true aurora, they must be driven by some form of particle precipitation. The “polar rain” described by Winningham and Heikkila in 1974 is a gentle and even rain of charged particles from the solar wind, guided in by the open field lines in the magnetosphere. (Winningham & Heikkila, 1974*)*. These polar rains, and various types of showers therein, are thought to drive the polar cap aurora, a different process than the auroral oval (Hosokawa et al., 2020).

**Figure 17**

*Transpolar arc (theta aurora)*



*Note.* This image sequence from the Far Ultraviolet Wideband Imaging Camera on the IMAGE spacecraft show the formation of a transpolar arc, or theta aurora, seen here as the vertical line that is most prominent in the middle image. It begins at the nightside of the auroral oval and stretches across the polar region towards the dayside. Image from Hosokawa et al. “Aurora in the Polar Cap: A Review” (2020), used with permission.

## Polar Cusp Aurora

Polar cusp aurora are a rare and highly localized phenomena, only visible in certain regions that are above the arctic circle, making observations of them rare and difficult. They are also the only form of aurora that is found on the dayside, centered on local noon. Before we can describe them, however, we must establish what the "polar cusp" itself is.

Earth's magnetic field forms the magnetosphere, which takes the form of a giant bubble around the planet, shielding us from the solar wind. Particles from the solar wind still reach the upper atmosphere to cause aurorae, but by an indirect means, not simply by blowing in from the solar wind. However, this direct entry does occur in only two specific places: the polar cusps (pictured in Figure 3). As was described back in 1972 by Heikkila and Winningham, the polar cusps can be thought of as two "holes" in the bubble that is the magnetosphere, taking the shape of a funnel with a very small point. These two points, the polar cusp regions, lie in the Arctic (and Antarctic) at local noon. The "funnels" allow charged particles from the solar wind to precipitate directly into the atmosphere, where they can cause the polar cusp aurora (Heikkila & Winningham, 1971).

Due to the polar cusps being found at local noon, this means the polar cusp aurora is a rare phenomenon of a dayside aurora, the only one in this review that is specific to the dayside (when the normal discrete aurora is particularly strong, it may expand dusk- and dawn-ward and enter the dayside, but not originate there). Since the polar cusps are in the region of the Arctic and Antarctic circles, the aurora is visible at noon in the winter when the sun does not rise at all. The polar cusp aurora is also highly localized, being specific to the small footprint of the polar cusps (Mende et al., 2016). In terms of visual appearance, the polar cusp aurora appears quite similar to normal discrete aurora, as seen in Figure 18 by NASA's Goddard Space Flight Center (2018). The polar cusp aurora, although formed by different mechanism than the normal aurora, has much the same end result of accelerated charged particles impacting the atmosphere, producing a similar result.

Similar to the auroral oval, proton aurorae can also form in the polar cusp region. As described by Bryant et al. (2013), like standard polar cusp aurorae these polar proton aurorae formed under northward directed IMFs, and take the appearance of "spots," similar to the SAMPs described by Frey (2007), far equator-ward in the auroral oval (Bryant et al., 2013).

**Figure 18**

*Polar cusp aurora*

*Note.* The cusp aurora seen from Svalbard, with a LIDAR beam in the foreground. Taken during a study by NASA scientists and engineers on the polar cusp aurora in December 2018. Photo by the NASA Goddard Space Flight Center on Flickr.com, https://www.flickr.com/photos/nasa_goddard/47668658881. Used under CC BY-NC-ND 4.0.

### Dunes Aurora

It's not often that a new form of aurora is discovered, but in 2020 Palmroth et al. described a new one: "the dunes." Appearing alongside a display of discrete aurorae in a zone of dim diffuse aurora, the dunes appear as finger-like rays extending horizontally out equatorward from the base of the discrete aurora, much dimmer than the bright bands. Citizen scientists report that the dunes are only faintly visible to the naked eye, becoming more vivid as imaged by a digital camera (Palmroth et al., 2020).

The display studied by Palmroth et al. (2020) was observed simultaneously from multiple locations in Finland, allowing the altitude of the dunes to be triangulated by referencing specific dunes in simultaneous images to background stars. The altitude of the dunes event was determined to be approximately 99 km. The area the dunes was observed in was from 65-80 degrees geographic latitude, which coupled with the 80-120 km altitude is an understudied region often termed the "ignorosphere," where spacecraft would need large amounts of thrust to maintain an orbit. The discovery of the dunes provides a new way to study this less accessible region. Using a similar method to that for determining altitude, the distance between dunes was estimated at 45 km, which is termed their wavelength.

Wavelength is an appropriate term, as Palmroth et al. hypothesized that the dunes are a manifestation of atmospheric waves of some sort. One possible wave could be gravity waves, and the north-south orientation of the dunes could align with a gravity wave source in the Scandinavian mountains. However, these waves are known to become distorted to a degree not seen in the regular spacing of the dunes, and gravity waves are common enough that if the only conditions to create dunes were gravity waves and a diffuse aurora, dunes should be observed much more frequently than they are (Palmroth et al., 2020).

Another possible cause is a rare phenomenon called "mesospheric bores", a thin inversion layer in the mesosphere that forms a duct for gravity waves (Dewan & Picard, 2001). This could allow the gravity waves to propagate for long distances without fading or distortion, as would be the case for standard gravity waves, and Palmroth et al. (2020) hypothesized this could be the driver of the dunes. This is significant because the standard method of studying these mesospheric bores is through their affects on airglow. They have never been observed in the auroral region, likely because any auroral emissions can wipe out dim airglow and lead to data being discarded. The discovery of the dunes could provide a new way to study mesospheric bores in a region where it was challenging to do so previously (Palmroth et al., 2020). A study of a large-scale dunes event by Grandin et al. (2021) further confirmed the likelihood of mesospheric bores as the cause of the dunes. This study also measured the drifting speed of the dunes for the first time, which they hypothesized was indicative of strong winds at that altitude during the event.

**Figure 19**

*Dunes aurora*

*Note.* The dunes aurora as pictured in Palmroth et al.'s 2020 study. The citizen scientist photographs are annotated with numbered circles highlighting the individual dunes. The bright bands and rays of the normal discrete aurora are seen at right. Used under CC BY 4.0.

## Conclusion

The aurora has many forms beyond the three common types. These run the gamut from extremely common and simply less flashy, such as the diffuse aurora, to rare and invisible to the naked eye: dunes aurora and SAR arcs, for example. Some of these forms have been documented since at least the 1970s, and some have only been described in the last few years, illustrating how much we still have yet to learn about the aurora. One pattern throughout is a time lag between when a form of aurora is known and documented by photographers, etc. and when it is studied by scientists. As the quality of consumer cameras, even camera phones, approaches scientific grade, their documentation becomes increasingly valuable for scientific research. Scientists have been slow to recognize this but are beginning to catch on, with more studies involving analysis of citizen scientists' data. This is a trend that should be continued and strengthened, as there is much to be learned from the extensive network of observations from aurora chasers and photographers worldwide.

Another newer trend is that of interconnectivity between some of the aurorae or related phenomena. One example of this is the discovery of a link between proton aurorae and SAR arcs by Nishimura et al. in 2022, a connection that had not previously been theorized. This inter-type research appears to be a relatively recent endeavor, and may turn up more new connections within our magnetosphere.

A wide-ranging and varied phenomenon, the aurora and Earth's magnetosphere offer a rich field for scientific study, with an established body going back decades. Auroral research has focused on those types that are either common or easy to observe, and then expanded to cover additional rarer types. Although well-researched, there are still new auroral morphologies and mechanics being discovered, some as recently as the last year. This illustrates that there is much left to learn in the field of geomagnetism.

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