Fig. 3-1. Aurora over Quartz Lake, AK, 06 Sep 1996. Jan Curtis.

Fig. 3-2. Auroras over Fairbanks, AK. Jan Curtis.

Wonders of the Atmosphere
Chapter 3: Auroras

3.1 Auroras and the Solar Wind

Of all the wonders of the atmosphere, the Aurora Borealis and Aurora Australis are perhaps the most awe-inspiring, lighting the otherwise dark night sky with fantastic moving displays of vivid colors (Fig. 3-1, Fig. 3-2). Much like snowflakes, no two auroras have the identical color, shape, and evolution, but all follow a similar cycle of growth, expansion and recovery. The importance of studying auroras goes beyond their beauty. They are caused by the same disturbances on the Sun, namely, Sunspots (Fig. 3-3), solar flares, and Coronal Mass Ejections (CME) that can present a hazard to sensitive electronics, disrupt communications, destabilize low satellite orbits, cause power grid electrical surges and upset GPS navigation.

Fig 3-3. Sunspots near solar max, 5 August 2024. For scale, the Earth would be about the size of the smallest spots. The huge sunspot at left eventually produced a strong geomagnetic solar storm and many auroras. Jan Curtis.

The aurora is the beautiful product of complex interactions between the solar wind, Earth's magnetic field, and the atmosphere. The solar wind consists largely of electrons and protons (i. e., ionized or split hydrogen atoms) that stream from the Sun's Corona out to space in all directions. The Earth is bathed in this solar wind, which would smash directly into Earth (eventually stripping away Earth's atmosphere) except that the electrically charged electrons and protons, are corralled and deflected by Earth's magnetic field into the shadow zone of night. The aurora results when highly energetic electrons, and to a lesser extent protons, approach the Earth's surface close enough to smash into the atoms and molecules of the upper atmosphere.

During quiet times the solar wind is a modest flow. At the distance of the Earth, mean proton speeds average almost 200 km/s. The velocity and concentration of the solar wind increases enormously during disturbances that are much more common and stronger around the peaks of the Sun's cycles. Sunspots, solar flares, and Coronal Mass Ejections (CME) expel torrents of protons and electrons from the Corona. The strength of the incoming CME is measured by the speed and density of the solar wind. Usually if the speed is ~500 km/s auroras may be visible at high latitudes. If the speed exceeds 1000 km/s, the mid-latitudes may see the lights. Huge solar outbursts travel up to 3000 km/s reaching us in 15 to 18 hours and the number of energetic protons reaching the Earth every second can increase by a factor of over 100,000 from the background rate. It is during these times that the most spectacular and widespread auroras occur.

3.2 Auroras and Earth's Magnetic Field

As the electrons and protons approach the Earth they encounter its magnetic field. Earth's magnetic field is created by convective and spinning motions in the liquid iron and nickel outer core. The field is closely but not exactly aligned with the geographic poles and drifts over time, now moving around 60 km/yr. (In 2024, the North Magnetic Pole was calculated to be at 85.9° N latitude.) The strength of the field averages about 0.5 gauss, or only about 0.5% the strength of magnets used as stickers on refrigerators. Near the Earth the shape of the field resembles that of a bar magnet and is close to a classical dipole (Fig. 3-4). Further out from the Earth, in the magnetosphere,

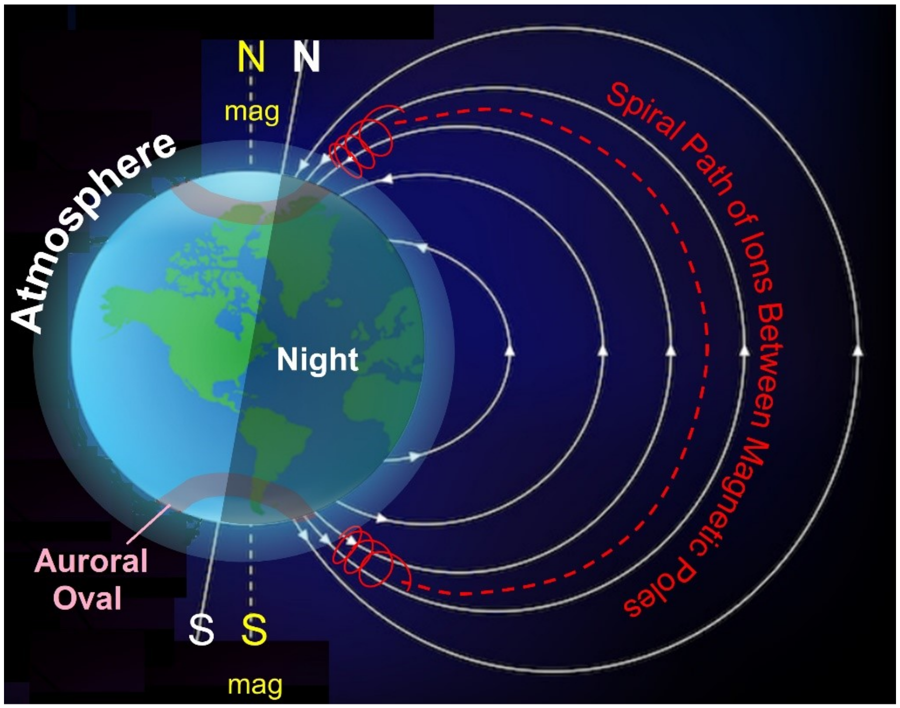

Fig. 3-4. The aurora, auroral oval, and Earth's magnetic field with spiral path of electrons along magnetic field lines between the magnetic poles. SDG.

Earth's magnetic field interacts with and is distorted by the solar wind and the interplanetary magnetic field it drags our from the Sun (Fig. 3-5).

When CME's approach the Earth they bombard the magnetosphere distorting and strengthening it, causing geomagnetic storms as well as auroras. The distorted magnetic field in turn deflects and accelerates the flow of electrons and protons, which have the best chance of pouring into the tail of the magnetosphere on the night side of the Earth when the interplanetary magnetic field (Bz) aims southward (opposite Earth's magnetic field) breaking and reconnecting the two fields to produce auroras, as illustrated in Fig. 3-4 and by the video,

https://vimeo.com/1001472030

The enhanced magnetic field during peak solar activity also reduces the rate at which harmful cosmic rays approach Earth's surface, which in turn reduces the production rate of radioactive Carbon-14 (^{14}C). Since plants ingest ^{14}C and are often preserved long after they die, they serve as proxies in the geologic record of past solar activity.

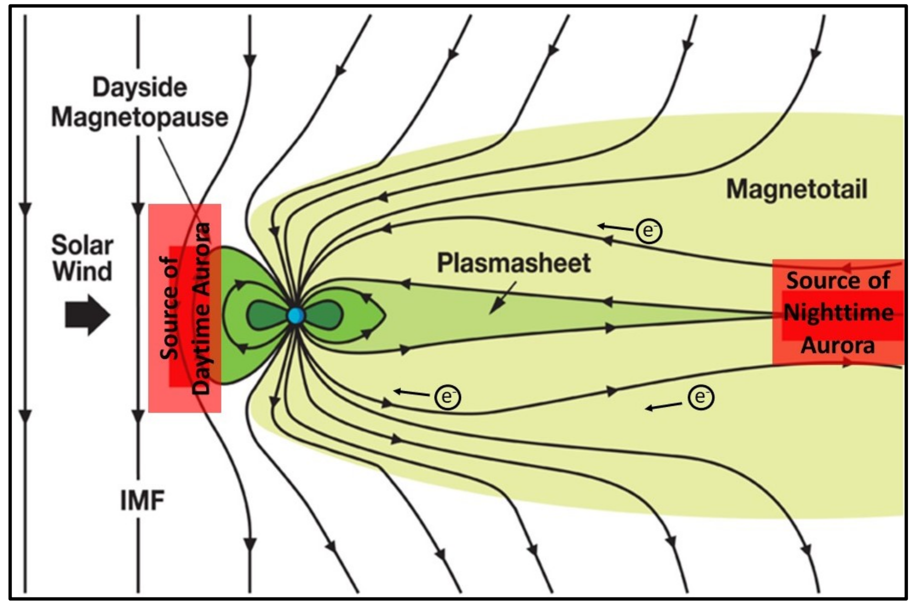

Fig. 3-5. Magnetosphere dynamics and auroras. (credit: ESA/ATG medialab)

After entering the magnetosphere, the electrons and protons are compelled to spiral along the magnetic field lines (as in Fig. 3.4) much like moths spiral around lights at night. For much of their stay, they remain so high above the Earth's surface that they essentially move through a vacuum. But the ions that have become trapped to spiral in the magnetic field lines that slope or dip sharply downward into the magnetic poles plunge down into the ionosphere and smash into its rarified gases.

This happens in the *auroral oval*, a ring around the magnetic poles that is confined to the high geomagnetic latitudes during quiet times, but broadens andspreads as solar activity increases, reaching the middle latitudes during huge CME's. A false color image of the auroral oval from an ultraviolet aurora around Antarctica was captured by NASA's IMAGE spacecraft on 11 Sep 2005 following a major CME (Fig. 3-6).

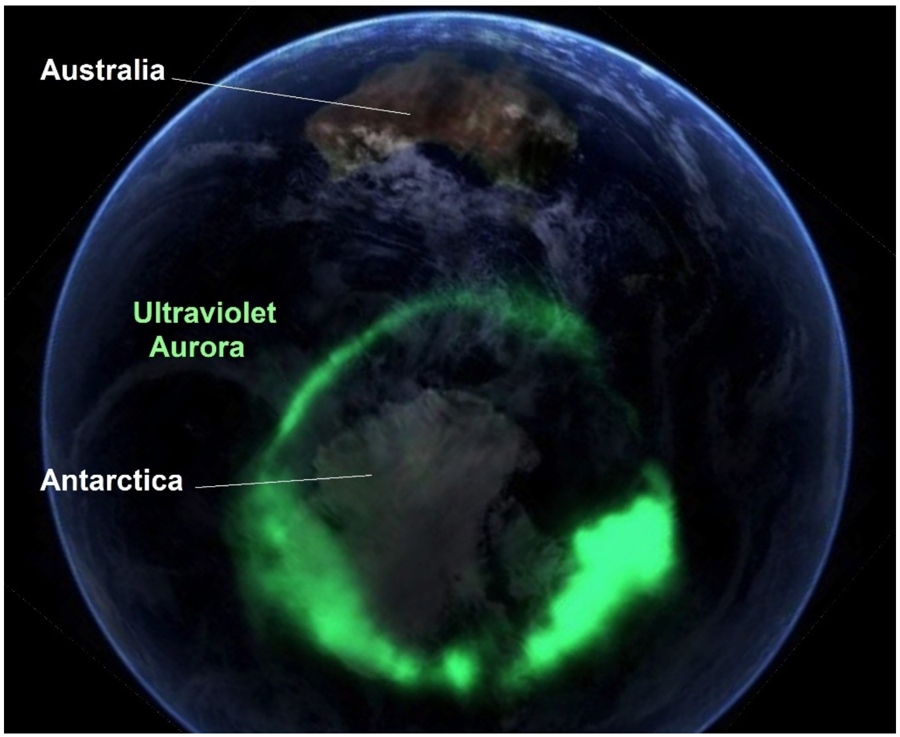

Fig. 3-6. False-color image of ultraviolet aurora australis around the auroral oval 11 September 2005. NASA IMAGE satellite, digitally overlaid onto The Blue Marble composite image.

Aurora *borealis* means *Northern* Dawn because in the middle latitudes it is most often seen reddening the sky at night just above the northern horizon. An example is the 'Deep Sky' aurora of 31 Dec 2024 in Cheyenne, WY (Fig. 3-7), which was accompanied by a rare Stable Aurora Red (SAR) arc. Deep sky auroras are barely visible to the unaided eye, but are revealed by time exposures of cameras.

Fig. 3-7. A "Deep Sky" aurora just above the horizon with a rare Stable Aurora Red (SAR) arc above, 31 Dec 24 from Cheyenne, WY. Jan Curtis.

Numerous space and terrestrial sensors are used to predict when and where auroras may be visible by measuring quantities including the flow and speed of protons, and the interplanetary magnetic field's direction and disturbances. The mean southern limit of the aurora is related to the Geomagnetic Storm Index, G, which ranges from 1 to 5, and the K-index of the outburst (Table 3-1). The K-index a measure of the maximum fluctuations of Earth's magnetic field observed on a magnetometer during a three-hour interval. It ranges from 0 to 9, with 5 or more indicating a geomagnetic storm. The planetary 3-hour-range index, Kp, is the mean standardized K-index from 13 geomagnetic observatories between 44° and 60° geomagnetic latitude.

Geomagnetic Storms

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Table 3-1. The strength and frequency of occurrence during the ~11 year Hale (sunspot) cycle is shown as an index of storm impacts.[1]

In the extreme cases when ***Kp*** = 9 the auroral oval is filled to overflowing so that auroras can be seen down to even lower latitudes, where they have stupefied people in ways that cannot be overrated. For example, George Siscoe has argued in ***Unleashing Yahweh: Ezekiel's Vision and the Northern Lights*** (2023) that the description of Ezekiel's Vision matches many of the features of the aurora, and its appearance was such a wondrous event that it firmed the faith among the Israelites then banished in Babylon. Modern sightings of the aurora at Honolulu, Hawaii (latitude 21°N) and even Colombia during the Carrington Event that peaked on 1-2 Sep 1859 (making the sky bright enough to read and causing fires in telegraph stations) confirmed the possibility of Ezekiel's sighting.

The contour lines in Fig. 3-8 give the mean equatorward position for a given Kp-index that the aurora borealis will fill the northern half of the sky. If the Kp-index is greater than the value of a line, the aurora will fill the entire sky at all points within that line. If the Kp-index is slightly less than the value of the line shows for a given location, the aurora may still appear low on the horizon; however, a perfect viewing location and good eyes are usually required to see it. This is when a camera is helpful to pick up fainter "Deep Sky" aurora displays.

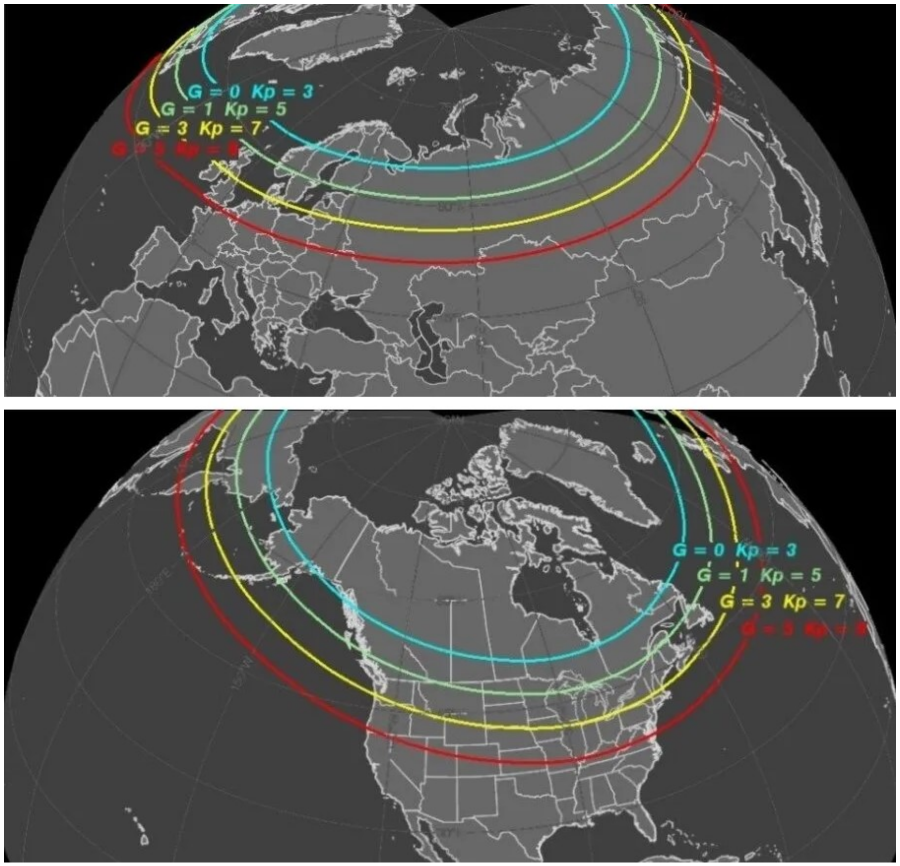

Fig. 3-8. Furthest south the aurora can be seen as a function of the Kp index. Source SWPC/NOAA, https://www.theaurorazone.com/nuts-about-kp/

The appearance and intensity of the aurora vary over the course of the night. Soon after the Sun sets in the west the aurora appears low on the eastern horizon. On average, the aurora appears highest and is brightest around midnight. As dawn approaches and the Sun begins to light the eastern sky, the auroras fade last near the western horizon. Of course, in the land of the midnight sun, auroras often brighten at noon although midnight remains the major peak time of the daily cycle.

3.3 Auroras and the Atmosphere

Auroras occur in the ionosphere, high above the Earth's surface. At the Earth's surface, even though air seems so light, molecules are packed so closely that a particle can only move about 1/10th of a micrometer before colliding with an air molecule. Light waves can skirt around the molecules but particles have no such ability and strike any other particle in their path. As electrons spiral from great heights down to the Earth, the rarified air is finally dense enough for collisions to occur about 300 km above the Earth's Surface, and even the most energetic electrons and protons in the strongest CME's are stopped by about 60 km above the Earth's surface.

Before the era of rockets and satellites the height of the auroras could only be determined by laborious triangulation of several different observers. Now, of course, auroras are observed in their full glory from top to bottom by astronauts in the International Space Station, which orbits the Earth at 400 km. Fig. 3-9 captured the full height of the aurora of 29 Aug 2014 from its green base to its red top, and showed how far it formed above the paper thin, dense lower atmosphere indicated by the blue stripe. The aurora's dynamism was captured in the video,

https://www.youtube.com/watch?v=WDmNsX6Y2wo

3.4 Colors of the Aurora

Fig. 3-9. Aurora 29 Aug 2014 from the International Space Station. Alexander Gerst, ESA astronaut. ESA/NASA.

The aurora's light and color arise after the electrons from CME's smash into the ions, atoms, and molecules in the ionosphere and energize or excite them. As might be expected, the two gases most responsible for auroras are Oxygen and Nitrogen, the two major gases in the atmosphere. The collisions can split N_2 and O_2 molecules into atoms, ionize the atoms by stripping electrons away, or raise the energy level or orbitals of the electrons. Photons of light are emitted when the electrons deexcite or return to lower energy levels. The wavelength or color of the emitted light is determined by the energy change between the orbitals.

Two of the major wavelengths or colors of the aurora are green, at 557.7 nm and red, at 630 nm. Both are produced by atomic oxygen but the orbital transition corresponding to producing the red takes so

Figure 3-10. Blue and violet auroral tops during astronomical twilight over Fairbanks, Alaska. Jan Curtis

long to occur that collisions with other particles tend to disrupt it except at the highest levels that auroras form, where collisions of molecules take equally long. The slow deactivation of the red color not only confines it to greater heights, it makes the red part of the aurora seem to move more slowly than the green.

Much below 100 km, atomic oxygen is rare, so the green aurora fades. Nitrogen molecules produce a range of blue and red auroral light with blue at 428 nm the dominant wavelength. Other colors arise as the result of differing combinations of the spectral colors.

Our eyes cannot always detect the colors in faint auroras. Lining our retinas are rod-shaped and cone-shaped photoreceptor cells. About 95% of our photoreceptors (about 100 - 125 million) are rods. They are great at helping you see in dim places, but they are not as good at fine details, and they cannot detect colors. Cones can detect colors but since they require more light to activate than rods, faint auroras often appear white to the naked eye. The sensitivity of the human eye varies with wavelength or color, being lowest at the violet and red ends of the visible spectrum and greatest near the center. As a result, red auroras are about 10 times more difficult to observe by the human eye (though not by digital cameras) than green auroras.

We begin our voyage of color starting with the highest auroras, which normally extend upward to about 400 km but may range as high as 1000 km. We then proceed to the lowest auroras, which cut off sharply at around 80 km.

Blue and Violet [300-400+ km]: Hydrogen and helium release blue and violet light at the top of the aurora. However, these colors are relatively faint and are not usually visible except under very dark skies or with strong solar storms. Also, because these gases are relatively rare, the light is diffuse. One particular aurora color is the result of excited nitrogen being further excited by sunlight. This "sunlit aurora" typically occurs at twilight and can be seen as a purplish color at the top of the auroral rays (Fig. 3-10).

Fig. 3-11. A high-altitude red aurora, 10 Oct 2024, during a major solar storm over Cheyenne, WY. Jan Curtis.

Fig. 3-12. Common yellow-green aurora at Fairbanks, AK. Jan Curtis.

Fig. 3-13. An unusual blue aurora at Fairbanks, Alaska. Jan Curtis.

Fig. 3-14. An unusual low deep red aurora that occurs very briefly during extremely active displays. At twilight at Fairbanks, AK Jan Curtis.

Red [300-400+ km]: Red light at the top of an aurora comes from slow deexcitation of O atoms. In the mid latitudes, sometimes only the red appears above the horizon line (Fig. 3-11).

Yellow-Green [100-300 km]: Vivid lime green is the most common color of the aurora. It comes from rapid deexcitation of O, and penetrates to the base of the ionosphere because collisions are too infrequent to disrupt it (Fig. 3-12). Much below 100 km there is so little atomic oxygen the green aurora often ends sharply.

Blue [100-300 km]: Excited nitrogen molecules ($N2+$) release blue light when they return to a more stable energy state. Whether an aurora is blue, blue-green, or yellow-green depends on the interplay of light from nitrogen ions and oxygen atoms (Fig. 3-13).

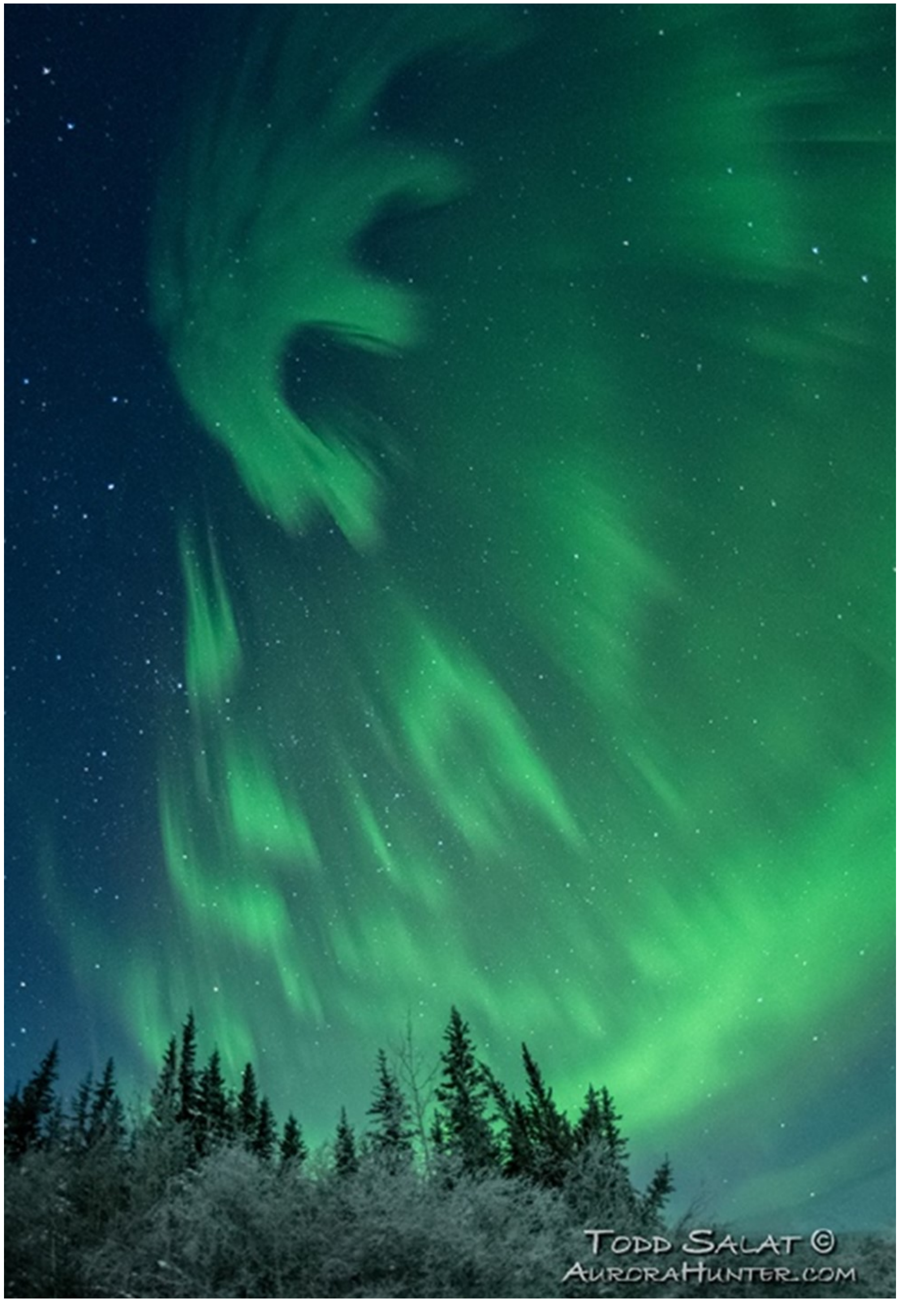

Fig. 3-15. Black "anti"aurora in Alaska. The "E" pattern shows voids that have eluded explanation until recently. ©Todd Salat / AuroraHunter.com)

Fig. 3-16. White aurora at Fairbanks, AK. Jan Curtis.

Deep Red [100 km]: A deep red color at the base of the aurora comes from deexcitation of N_2 (Fig. 3-14). The red fringe often changes color that last less than a second, making it difficult to image. Purple or vivid pink results when the red combines blue-violet light from deexcitation of N_2^+ ions. Orange results from the admixture of lime-green.

Fig. 3-17. Full spectrum aurora at Kõnnu Suursoo, Estonia. ©Andres Papp.

Black "anti" auroras (Fig. 3-15) are small-scale features embedded in the diffuse background aurora, typically occurring post-substorm after magnetic midnight and with an eastward drift. Black auroras show a significant reduction in optical brightness compared to the surrounding diffuse aurora and can appear as slow-moving arcs or rapidly moving patches and arc segments. The dark regions likely come from electric fields in the upper atmosphere that block electrons from interacting with gases.[10]

White auroras are very rare (even considered to be a hoax). However, this original un-processed image (Fig. 3-16) also observed, clearly shows that it exists and is the result of a perfect mix of many rarified atmospheric gases. Perhaps, digital camera sensors are unable to capture white aurora whereas film can. However, this still doesn't explain why visual sightings of pure white are not reported.

Multiple color auroras are the result of mixtures of the spectral colors to produce secondary colors (e. g., purple) and tertiary colors (e. g., vermilion - teal - chartreuse - amber). Thus, blended colors occur in strong geomagnetic storms. (Fig. 3-17).

3.5 Auroral Morphology and Structure

Auroras can be diffuse or discrete. Discrete auroras take on a range of shapes that extend into the fantastical including arcs, bands. curtains, coronas, and pillars or rays.

Arcs possess long graceful curves from horizon to horizon. They are the most common shape, seen in times of low solar activity. During times of more intense solar activity, they become more active and rippled or distorted. In mere minutes, arcs can change to bands and curtains.

Bands and Curtains are like arcs but appear with more curves. These wavy, ribbon-like aurora formations are the ones most people hope to see. When conditions get really intense, they may look like curtain folds blowing in the wind.

The changes from arcs to bands to curtains occur as (Alfven) waves in the moving plasma of charged particles waves in the magnetic field form and grow in amplitude (Fig. 3-18). The series of photos in Fig. 3-20 illustrates the amplification of waves in the aurora.

The apparent shapes of the aurora also depend on the viewing angle and the distance from the aurora (Fig. 3-19). Thus, for example, distant curtains may appear bandlike while curtains directly overhead will appear as coronas.

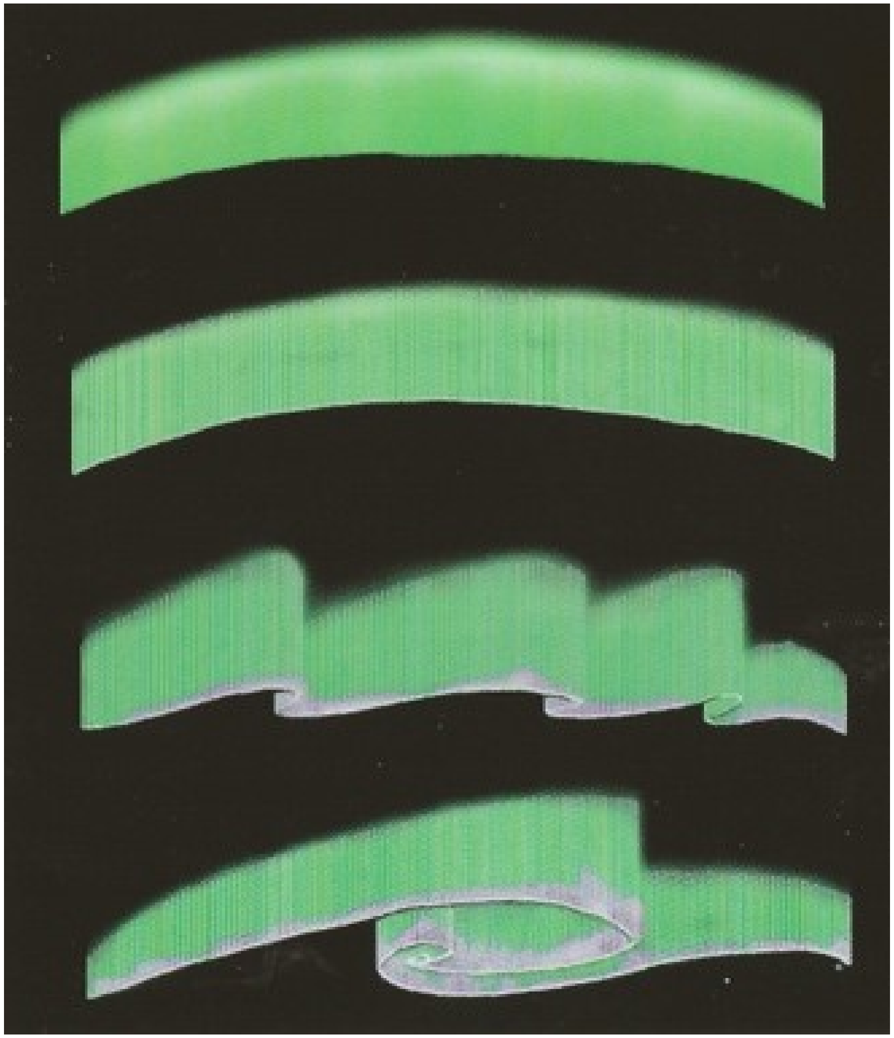

Fig. 3-18. Growth of waves changing an aurora shaped like band to an arc to a curtain. ©S. I. Akasofu.

Coronas are the most impressive of all auroras and have been the form most sought after by aurora chasers (at least until the discovery of dunes). This crazy, colorful vortex effect appears when you are standing directly under a display of pillars—when it happens, the base of the aurora is only about 80-90 km directly overhead. People have described coronas as looking like angels or butterflies or

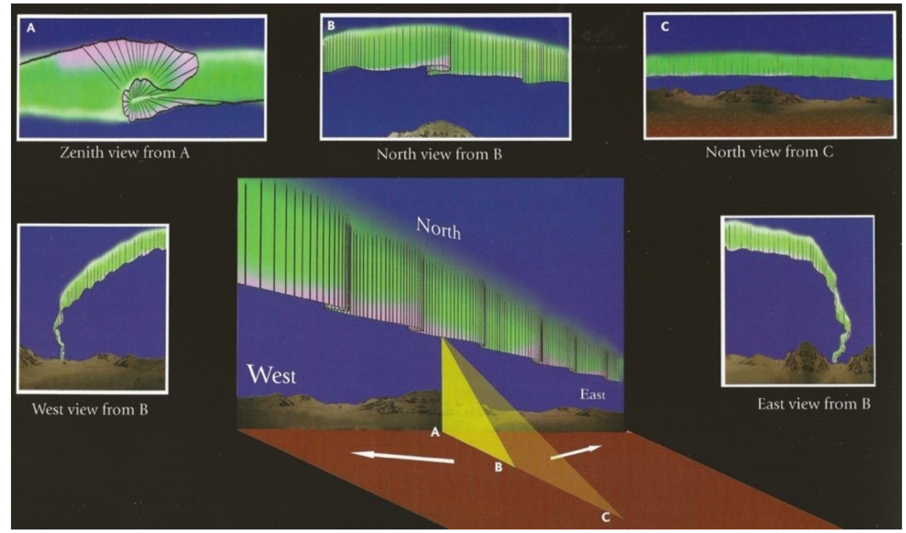

Fig. 3-19. Auroral curtain seen from various viewpoints and distances. ©S. I. Akasofu.

dragons. Since few auroras occur directly overhead, especially in the middle latitudes, corona auroras are rare. At high latitudes they are seen sporadically during periods of intense solar activity. In the mid latitudes they are only seen during exceptional, major solar events.

The sequence of photos in Fig. 3-21 captured a corona formation that developed directly overhead at Fairbanks, AK over a period of 30 seconds as auroral rays converged to the magnetic zenith. The ephemeral corona-shaped auroras usually coincide with the peaks of strong magnetic (or auroral) substorm events. The time lapse video of the Great May 10- 11, 2024 substorm, taken at Glendo, WY captured changes of the corona-shaped aurora every 10 seconds.

https://www.flickr.com/photos/cloud_spirit/53726786058

Pillars, also called beams or rays, can be seen alone as a streak or two, or as a cluster of streaks. They can also be features of active arc, band, or corona auroras. These are the vertical bars of light that seem to reach upwards (Fig. 3-22). They can sometimes be as tall as 600

Fig. 3-20. Auroral arcs transitioning into bands and curtains via growth of waves in the magnetic field lines and plasma. Fairbanks, Alaska. Jan Curtis.

km from the green base to the purple canopy. Their apparent upward convergence is largely a consequence of linear perspective.

Picket Fence auroras (Fig. 3-23) are of short duration and typically fast moving. They manifest as lines of separate parallel rays. They are often seen above a non-aurora event called STEVE (see below).

Pulsating auroras can change in appearances and intensity over a wide range of time scales, with periods of 2–20 seconds being typical. However, the changes may occur so slowly as to be difficult to notice, or too rapidly for the brain to detect. The flickering rate of 10 times per second is well known, but recent measurements show that auroras flicker at up to 80 times per second[14a]. A case of pulsating aurora was captured over a 20 s period during the peak of a G4 substorm on 10 Oct 24 over Cheyenne, WY (Fig. 3-24).

3.6 Auroral (Magnetospheric) Substorms

During solar storms, the magnetosphere fills to overflowing. Excess electrons then pour as from a tipping bucket as pulses corralled within the auroral oval down toward the Earth’s surface. These pulses, called magnetospheric or auroral *substorms*, last several hours and produce auroras that fill the sky within the auroral oval towards the magnetic poles. They have a typical life cycle of three phases, mapped in Fig. 3-25 and described below as if they take place over the course of a night, though they may occur several times in a night and even overlap.

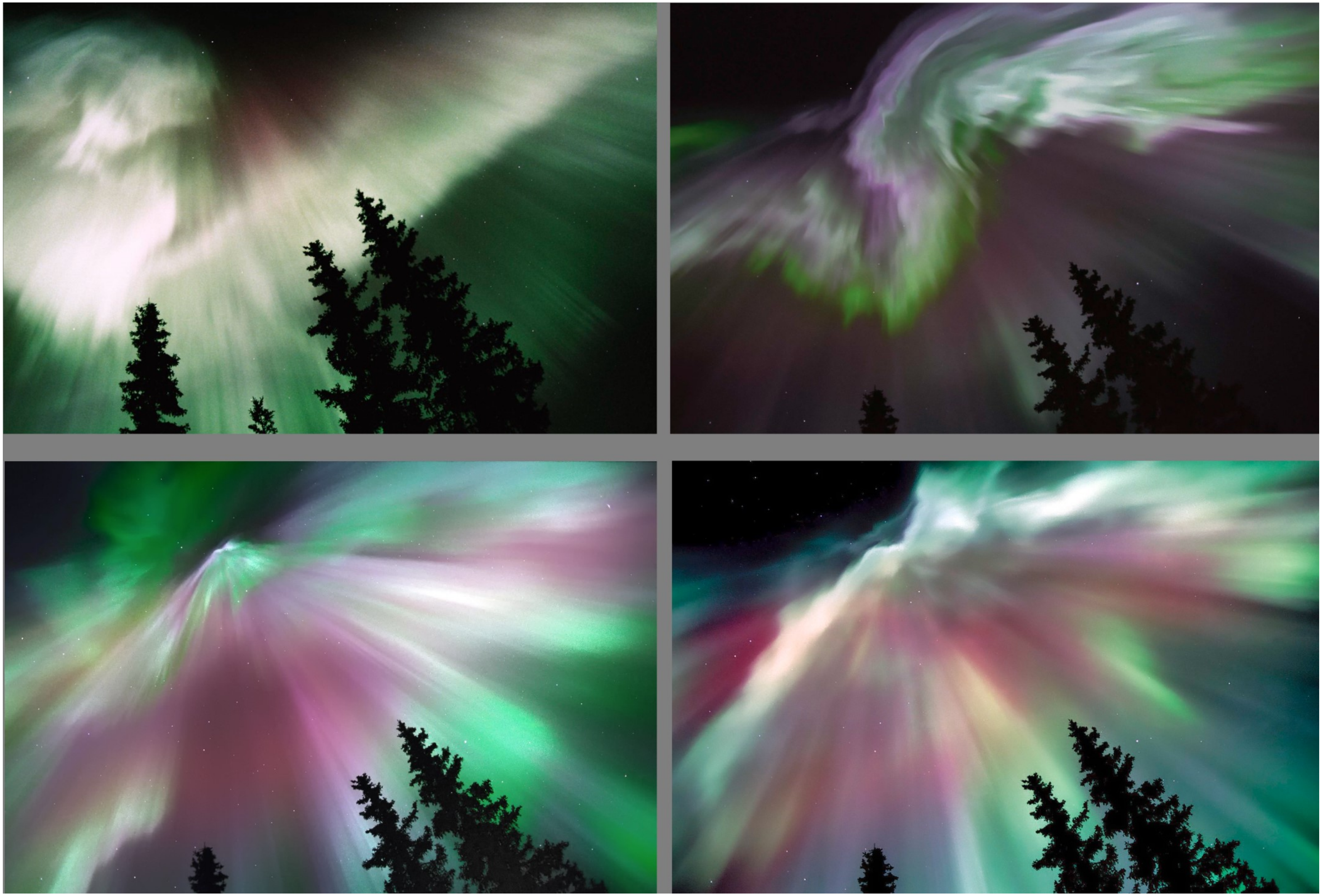

Fig. 3-21. Evolution of a corona aurora during a period of 30 s directly over Fairbanks AK. Jan Curtis.

Fig. 3-22. A pillar aurora minutes apart with a cluster of streaks at Fairbanks AK, 30 Mar 2001. Jan Curtis.

Fig. 3-23. Two cases of picket fence auroras lines of parallel rays, Fairbanks, AK. Jan Curtis

Fig. 3-24. Pulsating aurora during the peak of a G4 substorm on 10 Oct 24 over Cheyenne, WY, 20 seconds apart. Jan Curtis.

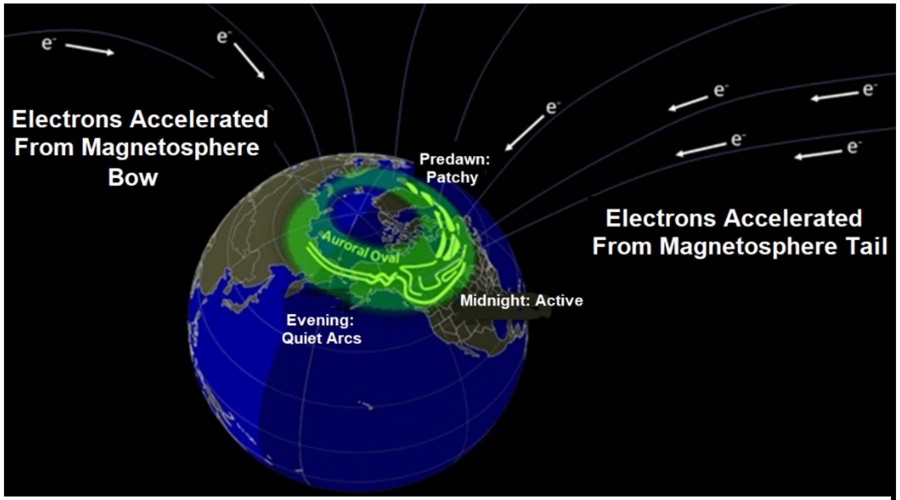

Fig. 3-25. Map of an auroral substorm that occurs over the course of a single night. SDG.

Fig. 3-26. Diffuse aurora at start of substorm . Jan Curtis.

Growth Phase (Evening): Shortly after sunset the aurora often appears as a diffuse arc (Fig. 3-26) spanning east-west from horizon to horizon. Sometimes there are several discrete parallel arcs (Fig. 3-27 left). Often, they appear as bundles of tall rays that resemble a hanging curtain. The evening arcs tend to fill the sky towards the poles to a degree that depends on the level of geomagnetic activity (Fig. 3-27 right). The motion[12] of the auroras is initially east to west. It slows by midnight, after which it reverses direction and accelerates as the auroral oval sinks to the western horizon.

Expansion Phase (Midnight): A few hours before midnight, depending on the level of geomagnetic activity, the aurora can show signs of increased activity in the form of waves or ripples that develop and move along the auroral arcs (Fig. 3-28 left) much like someone running their hand along a curtain. During periods of moderate to high geomagnetic activity, there can be a series of geomagnetic substorms that greatly enhance the complexity and brightness of the aurora for several hours around midnight. The aurora can rapidly expand poleward. Great swirls and bright features appear. Each substorm is associated with a "Westward Traveling Surge" (Fig. 3-28 right) where structures move toward the western horizon at several km/s.

Fig. 3-27. Aurora becomes more structured and spreads from the east horizon to its highest point in the sky around local midnight. Jan Curtis.

Fig. 3-28. Expansion phase. Waves amplify and move along auroral arc (left). Complex structures form and move rapidly to the west (right). Jan Curtis.

Fig. 3-29. Diffuse patches of aurora at Chena Hot Springs, AK. Jan Curtis.

Recovery Phase (Toward Dawn): After the substorms pass overhead, the aurora becomes less active, more diffuse and 'patchy' (Fig. 3-29). The patches often pulse on and off every 10 seconds (though they could strobe up to 80 times per second) and usually continue doing so until dawn. The 10 second period is too slow to create the sense of a pulsating patch except with time-lapse videos. As the substorm ends, the aurora dims and fades and is no longer so distinctive, sometimes resembling a predawn sky (Fig. 3-30).

Fig. 3-30. Diffuse auroral glow (not twilight) at end of substorm. Jan Curtis.

3.7 Auroral Outliers

Dune Auroras

Most auroras intrude themselves into a relatively passive atmosphere. Occasionally, winds can be so fast and waves so pronounced near the base of the mesosphere that they alter the shapes and motions of the auroras. This is the case with recently discovered (2016) dune auroras, which have distinctive shapes that resemble dunes (Fig. 3-31). Their shape and motions, animate in the video

https://www.youtube.com/watch?v=OMgsOyIuebc

are driven by gravity waves that rise from below, curve into the mesosphere and get trapped in anomalous temperature inversions between about 90 and 100 km The trapped waves then become supercritical and resemble tidal bores. The first documented case of dune auroras occurred on 20 Jan 2016. It was photographed by

Fig. 3-31. Dune aurora (left) at 100 km altitude with an auroral arc at Laitila, Finland 07 Oct 2018. ©Kari Saari.

scientist observers from Finland to Scotland, so its velocity could be calculated (to the WSW at 200 m/s).

STEVE

Fig. 3-32. A purple and green searchlight beacon of STEVE (possibly the southernmost case) on 17 May 2017 east of Cheyenne, WY. Jan Curtis.

Fig. 3-33. A stable Auroral Red Arc on 10 Oct 2024 at Boulder, CO. ©Bill Bowman.

In 2016, more than fifty citizen science observations described what was an aurora look-alike they named STEVE, for "Strong Thermal Emission Velocity Enhancement”. STEVE is not an aurora though it most often occurs in conjunction with picket fence auroras. It has been observed on and off for centuries, though was not named before 2016. STEVE occurs at an altitude of 450 km and consists of long, narrow (~25 km wide) purple and green ribbons (Fig. 3-32) of superheated plasma (***T*** ~3300 K) well above the typical high temperatures of ~2000 K in the excited thermosphere. The air is accelerated from typical speeds of 10 m/s to 6 ***km***/s. At that speed, collisions can split molecules. One hypothesis for the purple color is the energy released when nitrogen and oxygen combine to form nitric oxide. A video of the STEVE event of 17 May 2017 over Cheyenne, WY reveals an apparent clockwise spinning (opposite that of most tornadoes) of the pillars or beams.

https://www.flickr.com/photos/cloud_spirit/34869601832

Much remains to be discovered about the causes and mechanisms of STEVE. In recent years, it has been observed that STEVE may develop from Stable Auroral Red (SAR) arcs.[16]

Stable Auroral Red (SAR) Arcs

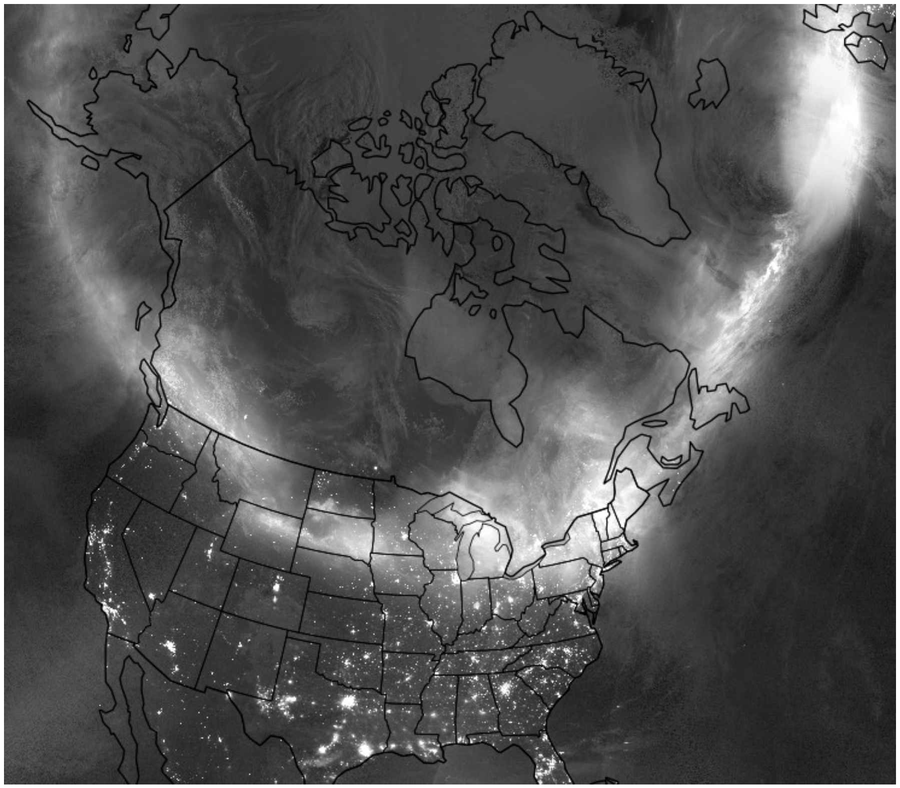

Fig. 3-34. Auroral oval on the night of 10-11 May 2024. VIIRS image.

Unlike the aurora which is generated by electrons smashing into Earth's atmosphere, Stable Auroral Red (SAR) arcs are generated by extreme thermal and kinetic heating from energy conducted from the electromagnetic field around Earth to the ionosphere. SAR arcs appear as relatively stationary east-west arcs. For unknown reasons, only oxygen is heated up during a SAR, which means these phenomena always emit the exact same shade of red. The SAR of Fig. 3-33, seen over Boulder, CO occurred during the strong G4 geomagnetic storm and associated aurora event of 10 Oct 2024. It appeared as a stationary red band rising from the west, distinct from the pillars of auroral color moving across the northern sky.

3.8 The Great Auroral Storm of 10-11 May 2024

On 08 May 2024 the world's aurora watchers were put on high alert as a giant X1-class flare and several other large solar flares burst out of the Sun producing Coronal Mass Ejections aimed toward Earth. The intensity of solar activity only grew more severe over the next several days, with an X4-class flare and giant CME's blasted out on 10 May that promised great things.

The night of 10-11 May lived up to its promise, producing the greatest and most widespread auroral display and the highest class of geomagnetic storm (G5) in decades. The aurora was seen as far south as the Yucatan, Jamaica, Cuba, and Hawaii, but, of course, the greatest displays were seen along the peaks of the auroral oval (Fig. 3-33), for example in Wyoming, South Dakota, Michigan, New York, and northern New England. And the Moon was 'cooperative' It was only two days past new so that it was only 12% as bright as a full Moon and set just before midnight.

Anticipating a major aurora, Jan travelled to Glendo State Park, WY, at the edge of Glendo Reservoir, where it was dark 160 km north of Cheyenne and 5 km from the nearest town lights, with a good view to the horizon. Setting up with multiple cameras that ran through the night until heavy dew fogged up the lenses after 0305 MDT, Jan recorded one of the greatest shows on Earth in an unintended selfie (Fig. 3-35) and the video,

https://www.youtube.com/watch?v=3pcji9Tz20Y&t=67s

Fig. 3-35. Aurora and selfie at Glendo State Park, WY on the night of 10-11 May 2024. Jan Curtis.

Fig. 3-36. Aurora's coat of many colors with Big Dipper (handle upper left) over Cheyenne WY 16 Sep 2024. Jan Curtis.