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Review of *Aurora borealis* spectacular manifestations of solar wind and atmosphere.

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ABSTRACT

Auroras frequently appear either as a diffuse glow or as curtains that extend approximately in the east–west direction. At some times, they form quiet arcs; at others, they evolve and change constantly. These are called active aurora. <u>Red:</u> At the highest altitudes, excited atomic oxygen emits at 630 nm (red); low concentration of atoms and lower sensitivity of eyes at this wavelength make this color visible only under more intense solar activity. <u>Green:</u> At lower altitudes, the more frequent collisions suppress the 630-nm (red) mode: rather the 557.7 nm emission (green) dominates. <u>Blue:</u> At yet lower altitudes, atomic oxygen is uncommon, and molecular nitrogen and ionized molecular nitrogen take over in producing visible light emission, radiating at a large number of wavelengths in both red and blue parts of the spectrum, with 428 nm (blue) being dominant. <u>Ultraviolet:</u> Ultraviolet radiation from auroras (within the optical window but not visible to virtually all humans) has been observed with the requisite equipment. <u>Infrared:</u> Infrared radiation, in wavelengths that are within the optical window, is also part of many auroras. <u>Yellow and pink:</u> Yellow and pink are a mix of red and green or blue.

In addition, the aurora and associated currents produce a strong radio emission around 150 kHz known as auroral kilometric radiation. X-ray emissions, originating from the particles associated with auroras, have also been detected. Aurora noise, similar to a hissing, or crackling noise, begins about 70 m (230 ft) above the Earth's surface and is caused by charged particles in an inversion layer of the atmosphere formed during a cold night.

The basic cause of auroras involves the interaction of the solar wind with the Earth's magnetosphere. The varying intensity of the solar wind produces effects of different magnitudes. The prime source of auroral particles is the solar wind feeding the magnetosphere, the reservoir containing the radiation zones, and temporarily magnetically trapped, particles confined by the geomagnetic field, coupled with particle acceleration processes.

Auroral arcs and other bright forms are due to electrons that have been accelerated during the final few 10,000 km or so of their plunge into the atmosphere. Protons are also associated with auroras, both discrete and diffuse. Auroras result from emissions of photons in the Earth's upper atmosphere, above 80 km (50 mi), from ionized nitrogen atoms regaining an electron, and oxygen atoms and nitrogen based molecules returning from an excited state to ground state. They are ionized or excited by the collision of particles precipitated into the atmosphere. Both incoming electrons and protons may be involved. Excitation energy is lost within the atmosphere by the emission of a photon, or by collision with another atom or molecule: Oxygen emissions green or orange-red, depending on the amount of energy absorbed. Nitrogen emissions blue or red; blue if the atom regains an electron after it has been ionized, red if returning to ground state from an excited state.

Bright auroras are generally associated with Birkeland currents, which flow down into the ionosphere on one side of the pole and out on the other. The solar wind and the magnetosphere, being two electrically conducting fluids in relative motion, should be able in principle to generate electric currents by dynamo action and impart energy from the flow of the solar wind.

Earth's magnetosphere is shaped by the impact of the solar wind on the Earth's magnetic field. This forms an obstacle to the flow, diverting it, at an average distance of about 70,000 km (11 Earth radii or Re), producing a bow shock 12,000 km to 15,000 km (1.9 to 2.4 Re) further upstream. The width of the magnetosphere abreast of Earth, is typically 190,000 km (30 Re), and on the night side a long "magnetotail" of stretched field lines extends to great distances (> 200 Re). The high latitude magnetosphere is filled with plasma as the solar wind passes the Earth. The flow of plasma into the magnetosphere increases with additional turbulence, density and speed in the solar wind. This flow is favoured by a southward component of the IMF, which can then directly connect to the high latitude geomagnetic field lines. Geomagnetic storms may vary with Earth's seasons. Two factors to consider are the tilt of both the solar and Earth's axis to the ecliptic plane.

The electrons responsible for the brightest forms of aurora are well accounted for by their acceleration in the dynamic electric fields of plasma turbulence encountered during precipitation from the magnetosphere into the auroral atmosphere. In contrast, static electric fields are unable to transfer energy to the electrons due to their conservative nature. One early theory proposed for the acceleration of auroral electrons is based on an assumed static, or quasi-static, electric field creating a uni-directional potential drop. Another theory is based on acceleration by Landau resonance in the turbulent electric fields of the acceleration region. Auroral electrons created by large geomagnetic storms often seem to have energies below 1 keV, and are stopped higher up, near 200 km. Such low energies excite mainly the red line of oxygen, so that often such auroras are red.

This paper deals with review of *aurora borealis* spectacular manifestations of solar wind and atmosphere which includes visual forms and colors of auroral radiation, aurora noise, causes of auroras, auroral particles, auroras and the atmosphere, auroras and the ionosphere, interaction of the solar wind with Earth, magnetosphere, auroral particle acceleration, various images of terrestrial auroras - aurora borealis.

Keywords: Aurora, Auroral particles, Earth, Solar wind, Atmosphere, Ionosphere, Magnetosphere, Aurora Borealis.

INTRODUCTION

An aurora sometimes referred to as polar lights, northern lights (aurora borealis) or southern lights (aurora australis), is a natural light display in the Earth's sky, predominantly seen in the high-latitude regions around the Arctic and Antarctic.

Auroras are perhaps the most spectacular manifestations of the complex interaction of the solar wind with the outer atmosphere. The energetic electrons and protons responsible for an aurora are directed by the solar wind along magnetic fields into Earth's magnetosphere.

The Earth's atmosphere, which is primarily made up of oxygen and nitrogen atoms, absorbs the heat from the solar wind when the particles collide with the oxygen and nitrogen atoms. This impact and the heat put the atoms in an excited state. When these atoms come back to their normal state, they release the excessive energy in the form of visible photons. These photons are what we see and name as the Northern Lights and Southern Lights. The Aurora phenomenon is not exclusive to Earth. The lights can be seen on any and all planets that have magnetic poles.

The portion of Earth that traverses the midnight portion of the auroral oval is known as the auroral zone. In the Northern Hemisphere this zone lies along a curve extending from the northern regions of Scandinavia through Iceland, the southern tip of Greenland, the southern region of Hudson Bay, central Alaska, and on to the coast of Siberia. This is the prime region from which to view an aurora in the Northern Hemisphere. The Aurora Australis is visible from high southern latitudes in Antarctica, Chile, Argentina, New Zealand, and Australia.

The most common type of aurora is associated with bombardment of the atmosphere by electrons with energies of up to 10,000 electron volts. Auroral displays are also produced by bombardment of the atmosphere by energetic protons. Protons with energies of up to 200,000 electron volts are responsible for auroral activity in a diffuse belt that is equatorward of the main auroral zone.

The magnetosphere includes two doughnut-shaped radiation belts, or zones, centred on the Equator that are occupied by appreciable numbers of energetic protons and electrons trapped in the outermost reaches of the atmosphere called Van Allen radiation belts.

Visual forms and colors

Auroras frequently appear either as a diffuse glow or as "curtains" that extend approximately in the east–west direction. At some times, they form "quiet arcs"; at others, they evolve and change constantly. These are called "active aurora".

The most distinctive and brightest are the curtain-like auroral arcs. Each curtain consists of many parallel rays, each lined up with the local direction of the magnetic field, consistent with auroras being shaped by Earth's magnetic field. In situ particle measurements confirm that auroral electrons are guided by the geomagnetic field, and spiral around them while moving toward Earth. The similarity of an auroral display to curtains is often enhanced by folds within the arcs. Arcs can fragment or break up into separate, at times rapidly changing, often rayed features that may fill the whole sky. These are the discrete auroras, which are at times bright enough to read a newspaper by at night. [1] and can display rapid subsecond variations in intensity. The diffuse aurora, though, is a relatively featureless glow sometimes close to the limit of visibility. [2] It can be distinguished from moonlit clouds because stars can be seen undiminished through the glow. Diffuse auroras are often composed of patches whose brightness exhibits regular or near-regular pulsations. The pulsation period can be typically many seconds, so is not always obvious. Often there black aurora i.e. narrow regions in diffuse aurora with reduced luminosity. A typical auroral display consists of these forms appearing in the above order throughout the night. [3]

Red: At the highest altitudes, excited atomic oxygen emits at 630 nm (red); low concentration of atoms and lower sensitivity of eyes at this wavelength make this color visible only under more intense solar activity. The low number of oxygen atoms and their gradually diminishing concentration is responsible for the faint appearance of the top parts of the "curtains". Scarlet, crimson, and carmine are the most often-seen hues of red for the auroras.

Green: At lower altitudes, the more frequent collisions suppress the 630-nm (red) mode: rather the 557.7 nm emission (green) dominates. Fairly high concentration of atomic oxygen and higher eye sensitivity in green make green auroras the most common. The excited molecular nitrogen (atomic nitrogen being rare due to high stability of the N_2 molecule) plays a role here, as it can transfer energy by collision to an oxygen atom, which then radiates it away at the green wavelength. (Red and green can also mix together to produce pink or yellow hues.) The rapid decrease of concentration of atomic oxygen below about 100 km is responsible for the abrupt-looking end of the lower edges of the curtains. Both the 557.7 and 630.0 nm wavelengths correspond to forbidden transitions of atomic oxygen, slow mechanism that is responsible for the graduality (0.7 s and 107 s respectively) of flaring and fading.

Blue: At yet lower altitudes, atomic oxygen is uncommon, and molecular nitrogen and ionized molecular nitrogen take over in producing visible light emission, radiating at a large number of wavelengths in both red and blue parts of the spectrum, with 428 nm (blue) being dominant. Blue and purple emissions, typically at the lower edges of the "curtains", show up at the highest levels of solar activity. [4] The molecular nitrogen transitions are much faster than the atomic oxygen ones.

Ultraviolet: Ultraviolet radiation from auroras (within the optical window but not visible to virtually all humans) has been observed with the requisite equipment. Ultraviolet auroras have also been seen on Mars, [5] Jupiter and Saturn.

Infrared: Infrared radiation, in wavelengths that are within the optical window, is also part of many auroras. [5, 6]

Yellow and pink: Yellow and pink are a mix of red and green or blue. Other shades of red, as well as orange, may be seen on rare occasions; yellow-green is moderately common. As red, green, and blue are the primary colours of additive synthesis of colours, in theory, practically any colour might be possible, but the ones mentioned in this article comprise a virtually exhaustive list.

Other auroral radiation

In addition, the aurora and associated currents produce a strong radio emission around 150 kHz known as auroral kilometric radiation (AKR), discovered in 1972. [7] Ionospheric absorption makes AKR only observable from space. X-ray emissions, originating from the particles associated with auroras, have also been detected. [8]

Aurora noise

Aurora noise, similar to a hissing, or crackling noise, begins about 70 m (230 ft) above the Earth's surface and is caused by charged particles in an inversion layer of the atmosphere formed during a cold night. The charged particles discharge when particles from the Sun hit the inversion layer, creating the noise. [9, 10]

Causes of auroras

A full understanding of the physical processes which lead to different types of auroras is still incomplete, but the basic cause involves the interaction of the solar wind with the Earth's magnetosphere. The varying intensity of the solar wind produces effects of different magnitudes, but includes one or more of the following physical scenarios.

A quiescent solar wind flowing past the Earth's magnetosphere steadily interacts with it and can both inject solar wind particles directly onto the geomagnetic field lines that are 'open', as opposed to being 'closed' in the opposite hemisphere, and provide diffusion through the bow shock. It can also cause particles already trapped in the radiation belts to precipitate into the atmosphere. Once particles are lost to the atmosphere from the radiation belts, under quiet conditions new ones replace them only slowly, and the loss-cone becomes depleted. In the magnetotail, however, particle trajectories seem constantly to reshuffle, probably when the particles cross the very weak magnetic field near the equator. As a result, the flow of electrons in that region is nearly the same in all directions ("isotropic"), and assures a steady supply of leaking electrons. The leakage of electrons does not leave the tail positively charged, because each leaked electron lost to the atmosphere is replaced by a low energy electron drawn upward from the ionosphere. Such replacement of "hot" electrons by "cold" ones is in complete accord with the 2nd law of thermodynamics. The complete process, which also generates an electric ring current around the Earth, is uncertain.

Geomagnetic disturbance from an enhanced solar wind causes distortions of the magnetotail ("magnetic substorms"). These 'substorms' tend to occur after prolonged spells (hours) during which the interplanetary magnetic field has had an appreciable southward component. This leads to a higher rate of interconnection between its field lines and those of Earth. As a result, the solar wind moves magnetic flux (tubes of magnetic field lines, 'locked' together with their resident plasma) from the day side of Earth to the magnetotail, widening the obstacle it presents to the solar wind flow and constricting the tail on the night-side. Ultimately some tail plasma can separate ("magnetic reconnection"); some blobs ("plasmoids") are squeezed downstream and are carried away with the solar wind; others are squeezed toward Earth where their motion feeds strong outbursts of auroras, mainly around midnight ("unloading process"). A geomagnetic storm resulting from greater interaction adds many more particles to the plasma trapped around Earth, also producing enhancement of the "ring current". Occasionally the resulting modification of the Earth's magnetic field can be so strong that it produces auroras visible at middle latitudes, on field lines much closer to the equator than those of the auroral zone.

Acceleration of auroral charged particles invariably accompanies a magnetospheric disturbance that causes an aurora. This mechanism, which is believed to predominantly arise from strong electric fields along the magnetic field or wave-particle interactions, raises the velocity of a particle in the direction of the guiding magnetic field. The pitch angle is thereby decreased, and increases the chance of it being precipitated into the atmosphere. Both electromagnetic and electrostatic waves, produced at the time of greater geomagnetic disturbances, make a significant contribution to the energising processes that sustain an aurora. Particle acceleration provides a complex intermediate process for transferring energy from the solar wind indirectly into the atmosphere.

The details of these phenomena are not fully understood. However, it is clear that the prime source of auroral particles is the solar wind feeding the magnetosphere, the reservoir containing the radiation zones, and temporarily magnetically trapped, particles confined by the geomagnetic field, coupled with particle acceleration processes. [11]

Auroral particles

The immediate cause of the ionization and excitation of atmospheric constituents leading to auroral emissions was discovered in 1960, when a pioneering rocket flight from Fort Churchill in Canada revealed a flux of electrons entering the atmosphere from above. [12] Since then an extensive collection of measurements has been acquired painstakingly and with steadily improving resolution since the 1960s by many research teams using rockets and satellites to traverse the auroral zone. The main findings have been that auroral arcs and other bright forms are due to electrons that have been accelerated during the final few 10,000 km or so of their plunge into the atmosphere. [13] These electrons often, but not always, exhibit a peak in their energy distribution, and are preferentially aligned along the local direction of the magnetic field. Electrons mainly responsible for diffuse and pulsating auroras have, in contrast, a smoothly falling energy distribution, and an angular (pitch-angle) distribution favouring directions perpendicular to the local magnetic field. Pulsations were discovered to originate at or close to the equatorial crossing point of auroral zone magnetic field lines. [14] Protons are also associated with auroras, both discrete and diffuse.

Auroras and the atmosphere

Auroras result from emissions of photons in the Earth's upper atmosphere, above 80 km (50 mi), from ionized nitrogen atoms regaining an electron, and oxygen atoms and nitrogen based molecules returning from an excited state to ground state. [15] They are ionized or excited by the collision of particles precipitated into the atmosphere. Both incoming electrons and protons may be involved. Excitation energy is lost within the atmosphere by the emission of a photon, or by collision with another atom or molecule:

Oxygen emissions green or orange-red, depending on the amount of energy absorbed.

Nitrogen emissions blue or red; blue if the atom regains an electron after it has been ionized, red if returning to ground state from an excited state.

Oxygen is unusual in terms of its return to ground state: it can take three quarters of a second to emit green light and up to two minutes to emit red. Collisions with other atoms or molecules absorb the excitation energy and prevent emission. Because the highest atmosphere has a higher percentage of oxygen and is sparsely distributed such collisions are rare enough to allow time for oxygen to emit red. Collisions become more frequent progressing down into the atmosphere, so that red emissions do not have time to happen, and eventually even green light emissions are prevented. This is why there is a color differential with altitude; at high altitudes oxygen red dominates, then oxygen green and nitrogen blue/red, then finally nitrogen blue/red when collisions prevent oxygen from emitting anything. Green is the most common color. Then comes pink, a mixture of light green and red, followed by pure red, then yellow (a mixture of red and green), and finally, pure blue.

Auroras and the ionosphere

Bright auroras are generally associated with Birkeland currents [16, 17], which flow down into the ionosphere on one side of the pole and out on the other. In between, some of the current connects directly through the ionospheric E layer (125 km); the rest ("region 2") detours, leaving again through field lines closer to the equator and closing through the "partial ring current" carried by magnetically trapped plasma. The ionosphere is an ohmic conductor, so some consider that such currents require a driving voltage, which an, as yet unspecified, dynamo mechanism can supply. Electric field probes in orbit above the polar cap suggest voltages of the order of 40,000 volts, rising up to more than 200,000 volts during intense magnetic storms. In another interpretation the currents are the direct result of electron acceleration into the atmosphere by wave/particle interactions.

Ionospheric resistance has a complex nature, and leads to a secondary Hall current flow. By a strange twist of physics, the magnetic disturbance on the ground due to the main current almost cancels out, so most of the observed effect of auroras is due to a secondary current, the auroral electrojet. An auroral electrojet index (measured in nanotesla) is regularly derived from ground data and serves as a general measure of auroral activity. Kristian Birkeland [18] deduced that the currents flowed in the east–west directions along the auroral arc, and such currents, flowing from the dayside toward (approximately) midnight were later named "auroral electrojets".

Interaction of the solar wind with Earth

The Earth is constantly immersed in the solar wind, a rarefied flow of hot plasma (a gas of free electrons and positive ions) emitted by the Sun in all directions, a result of the two-million-degree temperature of the Sun's outermost layer, the corona. The solar wind reaches Earth with a velocity typically around 400 km/s, a density of around 5 ions/cm^3 and a magnetic field intensity of around 2–5 nT (for comparison, Earth's surface field is typically 30,000–50,000 nT). During magnetic storms, in particular, flows can be several times faster; the interplanetary magnetic field (IMF) may also be much stronger. Joan Feynman deduced in the 1970s that the long-term averages of solar wind speed correlated with geomagnetic activity. [19] Her work resulted from data collected by the Explorer 33 spacecraft. The solar wind and magnetosphere consist of plasma (ionized gas), which conducts electricity. It is well known (since Michael Faraday's work around 1830) that when an electrical conductor is placed within a magnetic field while relative motion occurs in a direction that the conductor cuts across (or is cut by), rather than along, the lines of the magnetic field, an electric current is induced within the conductor. The strength of the current depends on the rate of relative motion, the strength of the magnetic field, the number of conductors ganged together and the distance between the conductor and the magnetic field, while the direction of flow is dependent upon the direction of relative motion. Dynamos make use of this basic process ("the dynamo effect"), any and all conductors, solid or otherwise are so affected, including plasmas and other fluids. The IMF originates on the Sun, linked to the sunspots, and its field lines (lines of force) are dragged out by the solar wind. That alone would tend to line them up in the Sun-Earth direction, but the rotation of the Sun angles them at Earth by about 45 degrees forming a spiral in the ecliptic plane), known as the Parker spiral. The field lines passing Earth are therefore usually linked to those near the western edge ("limb") of the visible Sun at any time. [20] The solar wind and the magnetosphere, being two electrically conducting fluids in relative motion, should be able in principle to generate electric currents by dynamo action and impart energy from the flow of the solar wind. However, this process is hampered by the fact that plasmas conduct readily along magnetic field lines, but less readily perpendicular to them. Energy is more effectively transferred by temporary magnetic connection between the field lines of the solar wind and those of the magnetosphere. Unsurprisingly this process is known as magnetic reconnection. It happens most readily when the interplanetary field is directed southward, in a similar direction to the geomagnetic field in the inner regions of both the north magnetic pole and south magnetic pole.

Magnetosphere

Earth's magnetosphere is shaped by the impact of the solar wind on the Earth's magnetic field. This forms an obstacle to the flow, diverting it, at an average distance of about 70,000 km (11 Earth radii or Re), [22] producing a bow shock 12,000 km to 15,000 km (1.9 to 2.4 Re) further upstream. The width of the magnetosphere abreast of Earth, is typically 190,000 km (30 Re), and on the night side a long "magnetotail" of stretched field lines extends to great distances (> 200 Re). The high latitude magnetosphere is filled with plasma as the solar wind passes the Earth. The flow of plasma into the magnetosphere increases with additional turbulence, density and speed in the solar wind. This flow is favoured by a southward component of the IMF, which can then directly connect to the high latitude geomagnetic field lines. [23] The flow pattern of magnetospheric plasma is mainly from the magnetotail toward the Earth, around the Earth and back into the solar wind through the magnetopause on the day-side. In addition to moving perpendicular to the Earth's magnetic field, some magnetospheric plasma travels down along the Earth's magnetic field lines, gains additional energy and loses it to the atmosphere in the auroral zones. The cusps of the magnetosphere, separating geomagnetic field lines that close through the Earth from those that close remotely allow a small amount of solar wind to directly reach the top of the atmosphere, producing an auroral glow. On 26 February 2008, THEMIS probes were able to determine, for the first time, the triggering event for the onset of magnetospheric substorms. [24] Two of the five probes, positioned approximately one third the distance to the moon, measured events suggesting a magnetic reconnection event 96 seconds prior to auroral intensification. [25]

Geomagnetic storms that ignite auroras may occur more often during the months around the equinoxes. It is not well understood, but geomagnetic storms may vary with Earth's seasons. Two factors to consider are the tilt of both the solar and Earth's axis to the ecliptic plane. As the Earth orbits throughout a year, it experiences an interplanetary magnetic field (IMF) from different latitudes of the Sun, which is tilted at 8 degrees. Similarly, the 23 degree tilt of the Earth's axis about which the geomagnetic pole rotates with a diurnal variation, changes the daily average angle that the geomagnetic field presents to the incident IMF throughout a year. These factors combined can lead to minor cyclical changes in the detailed way that the IMF links to the magnetosphere. In turn, this affects the average probability of opening a door through which energy from the solar wind can reach the Earth's inner magnetosphere and thereby enhance auroras.

Auroral particle acceleration

The electrons responsible for the brightest forms of aurora are well accounted for by their acceleration in the dynamic electric fields of plasma turbulence encountered during precipitation from the magnetosphere into the auroral atmosphere. In contrast, static electric fields are unable to transfer energy to the electrons due to their conservative nature. [26] The electrons and ions that cause the diffuse aurora appear not to be accelerated during precipitation. The increase in strength of magnetic field lines towards the Earth creates a 'magnetic mirror' that turns back many of the downward flowing electrons. The bright forms of auroras are produced when downward acceleration not only increases the energy of precipitating electrons but also reduces their pitch angles (angle between electron velocity and the local magnetic field vector). This greatly increases the rate of deposition of energy into the atmosphere, and thereby the rates of ionisation, excitation and consequent emission of auroral light. Acceleration also increases the electron current flowing between the atmosphere and magnetosphere.

One early theory proposed for the acceleration of auroral electrons is based on an assumed static, or quasi-static, electric field creating a uni-directional potential drop. [27] No mention is provided of either the necessary space-charge or equi-potential distribution, and these remain to be specified for the notion of acceleration by double layers to be credible. Fundamentally, Poisson's equation indicates that there can be no configuration of charge resulting in a net potential drop. Inexplicably though, some authors [28, 29] still invoke quasi-static parallel electric fields as net accelerators of auroral electrons, citing interpretations of transient observations of fields and particles as supporting this theory as firm fact. In another example, [30] there is little justification given for saying 'FAST observations demonstrate detailed quantitative agreement between the measured electric potentials and the ion beam energies...., leaving no doubt that parallel potential drops are a dominant source of auroral particle acceleration'.

Another theory is based on acceleration by Landau [31] resonance in the turbulent electric fields of the acceleration region. This process is essentially the same as that employed in plasma fusion laboratories throughout the world, [32] and appears well able to account in principle for most – if not all – detailed properties of the electrons responsible for the brightest forms of auroras, above, below and within the acceleration region. [33]

Other mechanisms have also been proposed, in particular, Alfvén waves, wave modes involving the magnetic field first noted by Hannes Alfvén (1942), which have been observed in the laboratory and in space. The question is whether these waves might just be a different way of looking at the above process, however, because this approach does not point out a different energy source, and many plasma bulk phenomena can also be described in terms of Alfvén waves.

Other processes are also involved in the aurora, and much remains to be learned. Auroral electrons created by large geomagnetic storms often seem to have energies below 1 keV, and are stopped higher up, near 200 km. Such low energies excite mainly the red line of oxygen, so that often such auroras are red. On the other hand, positive ions also reach the ionosphere at such time, with energies of 20–30 keV, suggesting they might be an "overflow" along magnetic field lines of the copious "ring current" ions accelerated at such times, by processes different from the ones described above. Some O+ ions ("conics") also seem accelerated in different ways by plasma processes associated with the aurora. These ions are accelerated by plasma waves in directions mainly perpendicular to the field lines. They therefore start at their "mirror points" and can travel only upward. As they do so, the "mirror effect" transforms their directions of motion, from perpendicular to the field line to a cone around it, which gradually narrows down, becoming increasingly parallel at large distances where the field is much weaker.

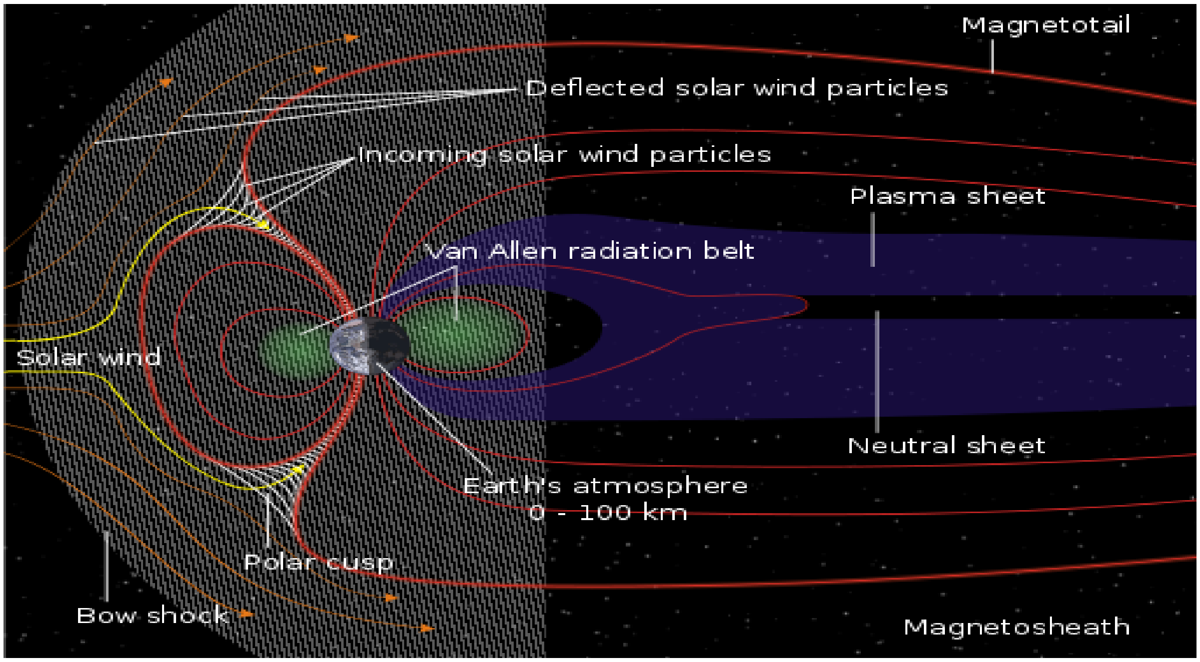

Figure 1. A simulation of a charged particle being deflected from the Earth by the magnetosphere. [21]

IMAGES OF TERRESTRIAL AURORAS - AURORA BOREALIS

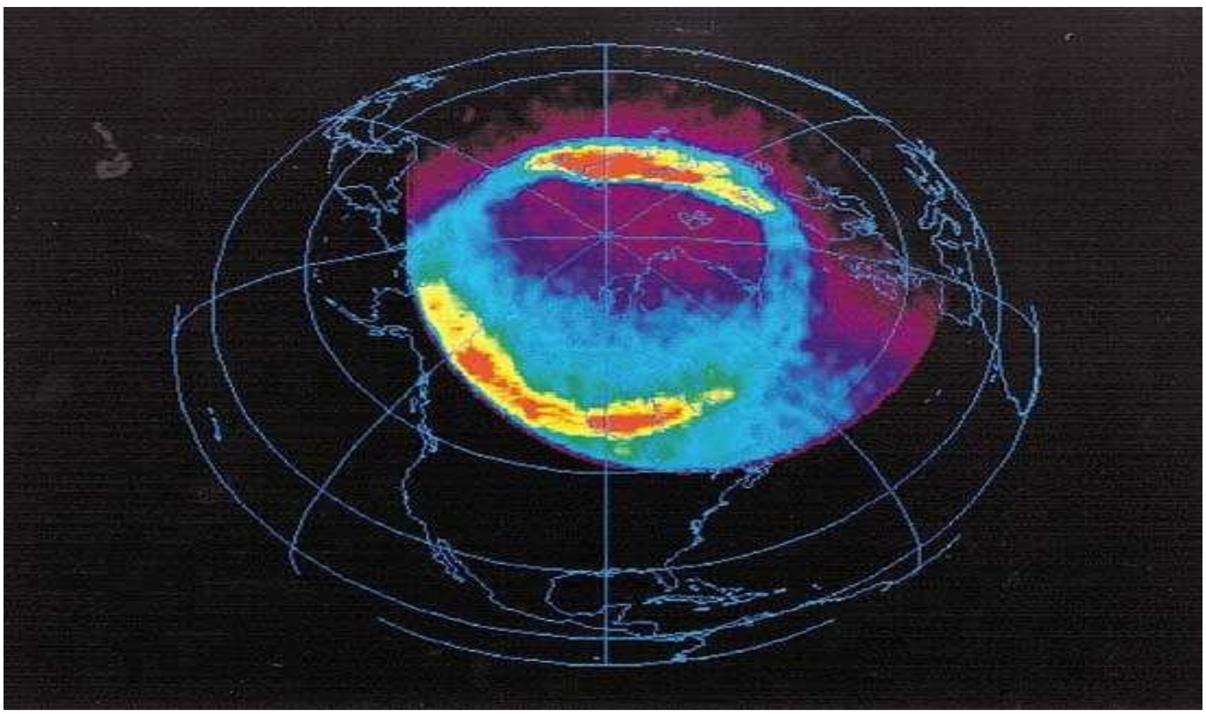

Figure 2. Earth's full North Polar auroral oval

Figure 3. Aurora image taken at Hillesoy island, Norway. September 2011. The bright moon are covered by the clouds. In the distance the light from the city of Tromsø (Tromsoe) shines in a faint orange color [35]

Figure 4. *Aurora Borealis* in Estonia 17.03.2015 [36]

Figure 5. *Aurora Borealis* in Estonia 18.03.2015 [37]

Figure 6. ***Aurora Borealis*** **in Estonia 18.03.2015 [38]**

Figure 7. ***Aurora Borealis*** **in Estonia 18.03.2015 [39]**

Figure 8. ***Aurora Borealis*** **in Estonia 18.03.2015 [40]**

Figure 9. ***Aurora Borealis*** **in Estonia 07.10.2015 [41]**

Figure 10. ***Aurora Borealis*** **in Estonia 07.10.2015 [42]**

Figure 11. ***Aurora Borealis*** **in Estonia 14.12.2015 [43]**

Figure 12. The Eyjafjallajökull and the aurora, seen from the Skogasandur outwash plain, near the village of Skogar(Over the Eyjafjallajökull glacier and volcano, Iceland) [44]

Figure 13. Northern Lights with very rare blue light emitted by nitrogen [45]

Figure 14. The Aurora Borealis, or Northern Lights, shines above Bear Lake [46]

Figure 15. Red and green Aurora in Fairbanks, Alaska [47]

Figure 16. Norther lights and the moon from southwestern Iceland (Moon and Aurora) [48]

Figure 17. ISS Expedition 6 team, Lake Manicouagan is visible to the bottom left

Figure 2 shows Earth's full North Polar auroral oval, in an image taken in ultraviolet light by the U.S. Polar spacecraft over northern Canada, April 6, 1996. In the colour-coded image, which simultaneously shows dayside and nightside auroral activity, the most intense levels of activity are red, and the lowest levels are blue. Polar, launched in February 1996, was designed to further scientists' understanding of how plasma energy contained in the solar wind interacts with Earth's magnetosphere. [34]

Figure 17 The *Aurora Borealis* or northern lights and the Manicouagan Impact Crater reservoir (foreground) in Quebec, Canada, were featured in this photograph taken by astronaut Donald R. Pettit, Expedition Six NASA ISS science officer, on board the International Space Station (ISS). [49]

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