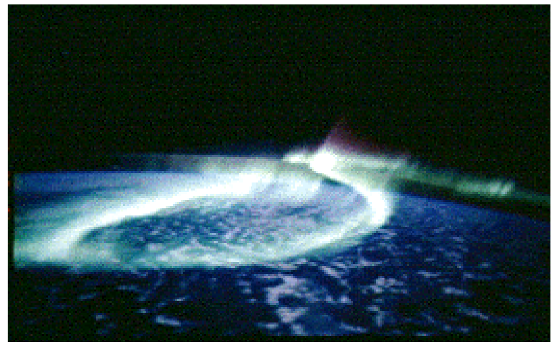
Aurora - Light of Mystery

What is aurora?


This shuttle image shows the characteristic oval shape of the aurora.[i]

Auroras, or polar lights, are the luminous phenomenon of the upper atmosphere occurs in high latitudes of both hemispheres. Auroras in the northern hemisphere are called aurora borealis and those in the south hemisphere are called aurora australis. Aurora (Latin for 'dawn') is beautiful and amazing lights which are visible in the dark sky in the poles. It can appear as many different forms, but usually it is a greenish quivering glow near the horizon. In 1621 the term 'aurora' was coined by the French astronomer. More and more observations were done and a concrete description was archived soon afterwards. Many theories were developed this phenomenon. Some suggested that it was the reflection of sunlight of artic light and some believed it was the firelight at the edge of the world; however both hypotheses are rejected because it was found that aurora was found 100-400km above the earth surface which is well beyond the atmosphere. Around the 17th century it has been discovered that it is caused by the interaction between energetic plasma particles from outside atmosphere with atoms of higher atmosphere. Till now, not all the questions about aurora have been answered, but with the escalating astronautic technology, we have a much better understanding on this puzzling phenomenon.

How does aurora form?

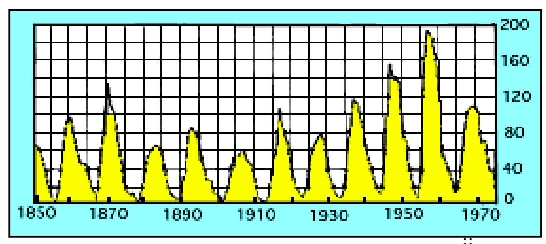
At every moment the sun is giving out charged particles in solar wind. Some of these particles are captured by the earth magnetic field and the bombardment of the solar wind with the atmospheric particles in the poles will then gives out energy as light. However this is just the basic principle of the formation of aurora, there are many more mechanisms going on at the same time which when they add up together will give rise to this stunning phenomenon.

Earth and its outer space

It is commonly believed that earth lies in an empty space in the universe which is vacuum. This is not absolutely true because vacuum is a space with nothing, no even air, but there are actually particles existing in the interstellar space. At sea level the density of air molecules is 1 quintillion per cm^3; at 100km roughly where aurora occurs, density is 1 trillion per cm^3; in the interstellar space the density is merely 1 per cm^3. Therefore as a result, most of outer space is filled with electrically conductive plasma. Besides of particles, there are magnetic field, electric current, electromagnetic force, gravitational forces… It is these invisible, but important factors which give rise to the interaction between the sun and the earth.

Sun and solar wind

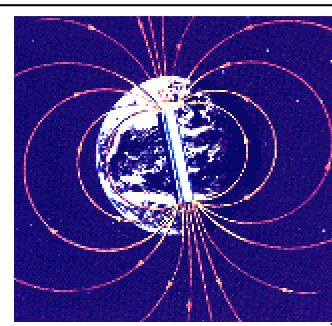
The sun is like a burning furnace which as a temperature as high as one million degrees. The light and heat energy comes from the interior nuclear fusion. At this temperature molecules like hydrogen on the sun surface will form plasma particles. Plasma is the fourth state of matter which occurs in extremely high temperature which is on the order of 10000°C. The temperature of the sun surface is about 5500°C and the temperature of the inner core is approximately 15000000°C, therefore all matter exists as plasma in the sun. In this state particles disintegrate into its constituent atoms and atoms may further decompose into proton and neutron. These charged particles are emitted continuously from the sun in all directions as the particles are too hot and the sun's gravity can no longer hold it down. This forms the solar wind. As the solar wind leaves the sun, it picks up the local magnetic field which contributes from the sun spots and the sun's magnetic poles which forms the Interplanetary Magnetic Field which is perpendicular to the direction of solar wind. The wind together with the weak magnetic field travels in a speed of 400km/s so they can make the trip to the earth in only a few days. The output of the plasma particles is affected by the coronal mass emission, sun spot and solar flares so its intensity varies from time to time. As the number of sun spots rises and drops in an irregular cycle of 11 years. At each peak the violent energy is given out from the sun spots and the aurora activities on earth will be much stronger than usual.



Sunspot Cycle (1850 – 1975) [ii]

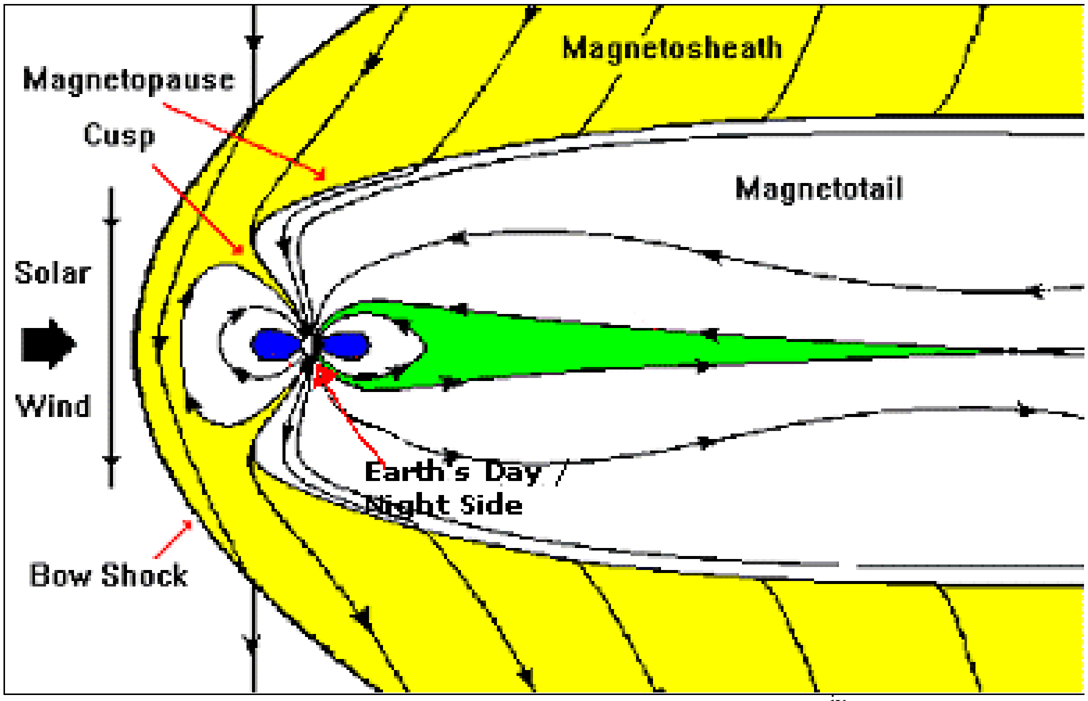
Earth's magnetic field

The earth has a bipolar magnetic field which means the field has two poles, north and south. The lines of magnetic force emerge from the South Pole and reenter in the North Pole, forming a symmetrical pattern just like a bar magnet. The more concentrated the field lines are, the stronger the magnetic force. Despite the existence of the magnetic field, it has little influence to our everyday environment because most of the materials we encounter in everyday life are electrically neutral. In fact this field has been protecting the earth's atmosphere by stopping the solar wind in a magnetic shock wave. Without this magnetic field, the atmosphere will be exposed to the high-energy solar wind and the solar particles will strip the air of the earth.



The Earth's magnetic field [iii]

Solar wind, magnetosphere and magnetic reconnection



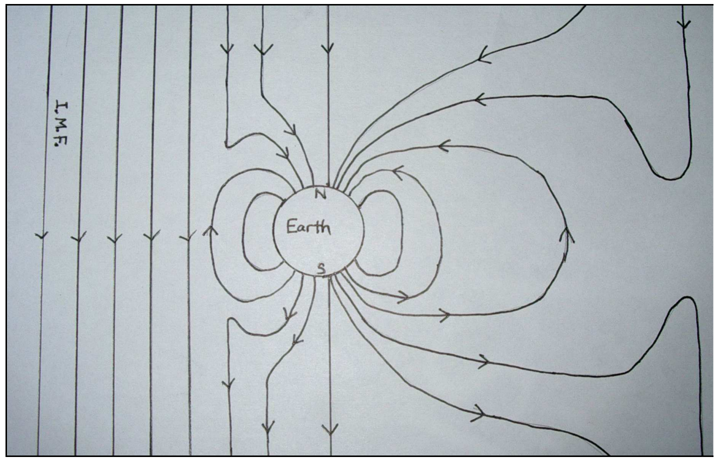
Artist's impression on Earth's magnetosphere [iv]

When the solar wind approaches the Earth's magnetic field, it will compresses the magnetic field lines facing it on the day side of the Earth and confines those lines into loops; it stretched those field lines on the night side and turn them into a long cylinder which is called the magnetotail. The magnetic fields are divided into two parts, the close and open loops. This shaped region of magnetic field is called the magnetosphere. In the areas where two regions join are the cusps over the north and south poles. Cusps are parts of magnetosphere which are directly opened to the solar wind.

The shape of the magnetosphere is contributed by the interaction between the Interplanetary Magnetic Field (IMF) and the earth's magnetic field. As the solar wind approaches the Earth, it will try to drag the earth's magnetic field just as it does to the Sun's. However as the earth's magnetic field is much stronger than the earth so the solar wind can only morph into a compact dayside section and a stretched night side tail. The magnetotail extends away the sun into the outer space and it has been observed that it extends at least 20 times the radius of the Earth.

As the earth is shielded by its bubble–like magnetic fields on the dayside, the encounter of the solar wind with the magnetosphere will create a shock wave. Plasma particles from the sun will be deflected by the magnetopause and flow around the comet-shaped magnetosphere. The earth and its magnetic field lie within this magnetic cocoon which protects us from the solar wind. This happens because when a charged particle travels across magnetic fields a force is created and will deflect the particle around the earth. Most of the solar particles are repelled and only about less than 1% of the particles will enter the magnetosphere.

The region between the solar wind and the magnetosphere is the magnetopause. It is the where the pressure of the geomagnetic field balances the solar wind. During magnetic storm, the magnetopause is pushed further towards the earth and this will make the particles from the wind to rush towards the earth's night side in a backlash. This increase in particles inflow into the magnetosphere will increase the aurora activity. The space between the bow shock and the magnetosphere boundary is known as the magnetosheath. Because after experiencing the shock, the magnetosheath plasma particles are usually slower and hotter as kinetic energy of the particles are converted into thermal energy.



Magnetic Reconnection

The solar wind continue to travel after passing the earth along the magnetopause, then the IMF will connect the perpendicular earth's magnetic field. This phenomenon is called magnetic reconnection. It has important effect on the formation of aurora as this allows the deflected solar particles to be redirected back to the magnetosphere and lead to the creation of aurora. The earth's magnetic field lines go from the South Pole to the North Pole and it is north pointing. The south-pointing IMF will therefore reconnect the northern part of the geomagnetic field; the southern part of the geomagnetic field will reconnect to the south-pointing IMF. However when the IMF is north-pointing, the magnetic reconnection will be much weaker and less particles will enter the magnetosphere. That's why aurora usually occurs when the IMF is pointing southwards. Magnetic reconnection happens in both sides of the earth, day and the night sides, but aurora is usually observed in the night side so the night side magnetic reconnection will be more useful for aurora research.

<u>Motion of charged particles in magnetic and electric field</u>

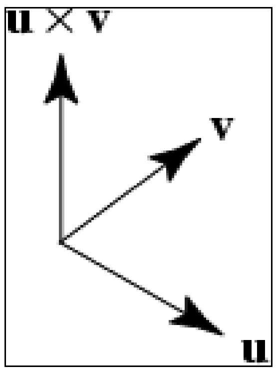
Now we understand that how the plasma particles travel from the sun to the earth's magnetosphere, however this still couldn't explain why the solar particles can end up in the poles where they interact with the earth's atmosphere to form aurora. Solar particles are mainly H^+, He^{2+} and electrons in plasma state. They conduct electricity readily and act like a conductor in the space. In fact solar particles are guided by some fields to the poles and in order to continue the exploration on aurora, we have to understand how the motion of charged particles is affected in magnetic and electric field.

The motion of charged particles in these fields can be explained by the Lorentz equation:

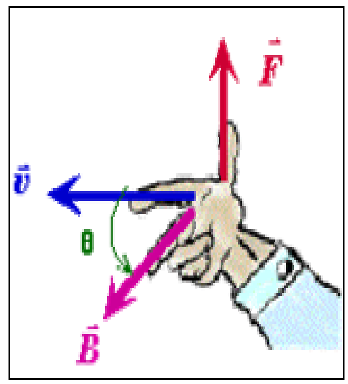
$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B} \times \sin\theta)$$ [vi]

which reads:

F: the force of the particle
q: the charge of the particle
E: the sum of the electric field
v: the velocity of the particle
B: the magnetic field
θ: the angle between the velocity of the charged particle and the magnetic field

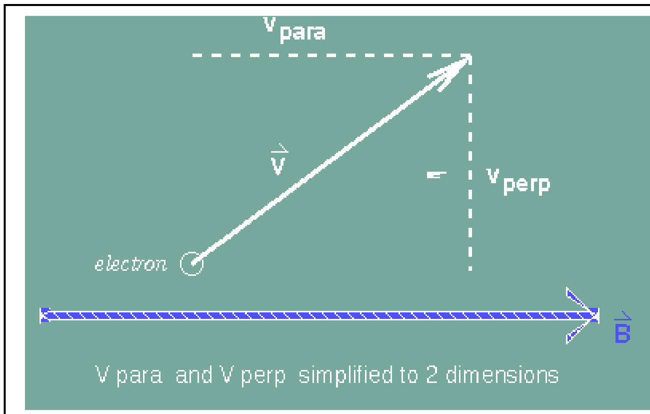


Cross-product of 2 vectors [vii]



right hand rule [viii]

It is easy to predict the interaction between a charged particle and an electric field because it is either repelled in the opposite direction or attracted to the direction of the field, depending on the charge of the particle. However the direction of force caused by the magnetic field is trickier because both **v** and **B** are both vectors so the force will be a cross-product. A cross product of two vectors (**v** & **B**) produces a third vector (Magnetic force) which is perpendicular to both of the initial vectors. With the right hand rule we can represent the 3 vectors respectively. By holding the right hand in a pistol shape, the middle finger represents the magnetic field, pointer finger represents the velocity and the thumb represents the magnetic force. Let's say there is an electron traveling in an angle across a magnetic field with a certain velocity as shown:

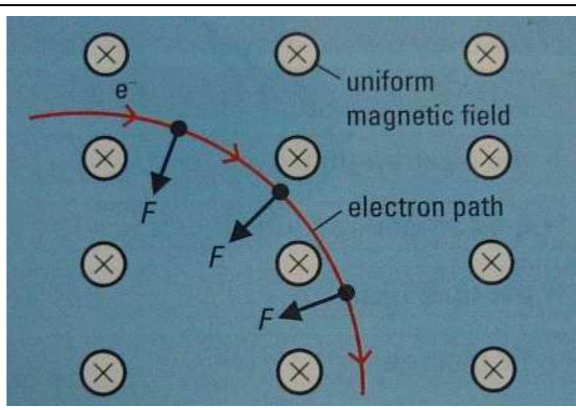


[ix]

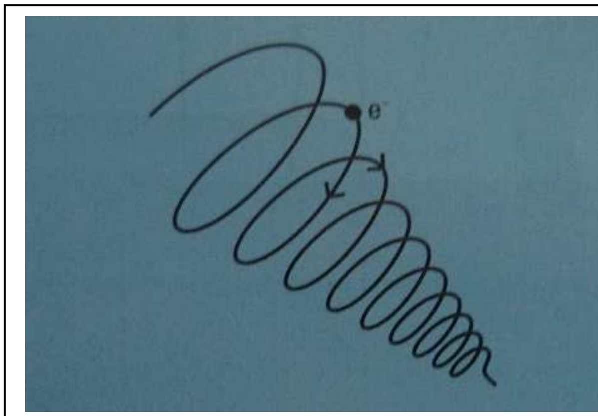
For simplicity, we will consider the magnetic field only in this case. We first resolve the velocity into the parallel and perpendicular components with respect to the magnetic field. Let's consider the each component and the Lorentz equation separately. For $\mathbf{v}_{para}$, the velocity is parallel to the magnetic field so the angle between two vectors is zero. This makes the magnetic force on the particle caused by this velocity component zero. Now let's consider the perpendicular component. The angle between the magnetic field and the velocity is 90°, so the magnetic force will be greatest. This is because the largest value the sin function can give is 1 which is equal to sin (90°).

For the parallel component:	For the perpendicular component:
$\mathbf{F} = q \times \mathbf{B} \times \mathbf{v}_{para} \times \sin(0)$	$\mathbf{F} = q \times \mathbf{B} \times \mathbf{v}_{perp} \times \sin(90)$
$\mathbf{F} = q \times \mathbf{B} \times \mathbf{v}_{para} \times 0$	$\mathbf{F} = q \times \mathbf{B} \times \mathbf{v}_{perp} \times 1$
$\mathbf{F} = 0$ N	$\mathbf{F} = q \times \mathbf{B} \times \mathbf{v}_{perp}$ N

From the equation we can see that the magnetic force is dependent on the perpendicular velocity component with respect to the magnetic field. The larger that velocity is, the larger the resultant force will be. Moreover the strength of magnitude field and the charge of the particle also affect the resultant force. **F** will cause **v** to change direction. However when **v** is changing, it will constantly have a perpendicular component to the magnetic field. This constant perpendicular force to the velocity will create a centrifugal force and keep the particle spinning in circle on the plane perpendicular to the magnetic field. This happens because the direction of the magnetic force changes as the velocity varies. When the charged particle approaches the magnetic field perpendicularly, it will keep on rotating on the same plane around the field, however in real life situations it is more likely that the particles will approach the field in angles rather than 90°, so the particle will travel in a spiral shape along the magnetic field.



The direction of the magnetic force acting on a moving electron changes as the electron's direction of the motion changes [x]



In three dimensions, the spiral is actually helical, because the particle's motion is not exactly at 90° to the magnetic field direction [xi]

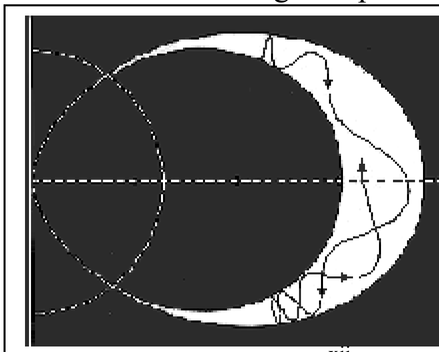
In a uniform magnetic field, charged particles will spiral around the magnetic field and as it rotates, it is traveling along the magnetic field line. However there are two ways of rotating, clockwise and anticlockwise. The direction of the spin is determined by the charge factor (q). Therefore a positively charged particles with +q will spin in opposite direction as the negatively charged particles with –q. The direction it is spinning depends both on the direction of magnetic field and the charge of the particles. With the right hand rule, we can find out which way the particle is spinning: first you form the finger cross-product with velocity, force and magnetic field. Then you rotate your hand in the direction of the force, keeping the direction of magnetic field the same. The particle will rotate in that direction as your hand does.

Therefore charged particles don't end up in he poles by random movement, but are guided by the magnetic field. This isn't solely how a constant influx and outflux of charged particles are created, as there are also some other processes going on at the same time.

Solar particles and interplanetary field

The earth is surrounded by the atmosphere which is mainly formed by neutral gases such as nitrogen, oxygen and hydrogen. Above the atmosphere (>90km) is the ionosphere which is formed by charged particles. There is no defined boundary for the ionosphere and it stretches out into the space. In the ionosphere there is enough energy from the solar UV light to ionize the neutral particles in the atmosphere which forms positively charged particles like O^+,N_2^{2+},O_2^{2+}… These ions with the electrons form plasma in the ionosphere. It is possible that the oxygen and nitrogen ions will recombine with the electrons to turn back to neutral molecules; however as the UV light is constantly fed to the ionosphere in the day time, so it will keep the temperature high enough for the plasma to exist. In the night time some of the ions turn back to molecules. The other source of charged particles in the ionosphere is the solar particles which enter the magnetosphere.

Less than 1% of the solar particles enter the magnetosphere where they are trapped there by the magnetic field or the magnetic bottles. They will either spiral around the magnetic field lines or bounce back and forth at the mirror region where the strong magnetic field converges and creates repulsion. Some of these particles will travel to the poles producing a current driven by a potential drop produced by the electrostatic shock. However how can this happen? The question was partly answered by a Norwegian physicist, Kristian Birkeland. He has observed that aurora arcs usually extend from the east to the west and he believed that there is a current flowing long them. Indeed this has been proven to be true by the satellites and it is called the Birkeland currents. He proposed that a current came down from space at one end of the arc and left in the other end and it is the ionosphere which connects the circuit. However there is another theory which is suggested to explain this current as well.



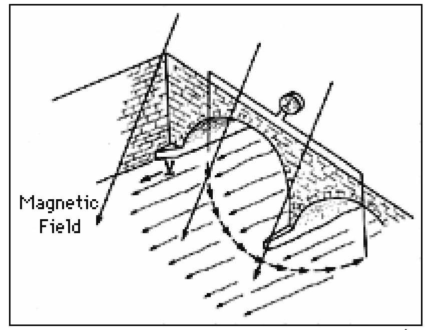
Magnetic bottle [xii]

Faraday's Law states

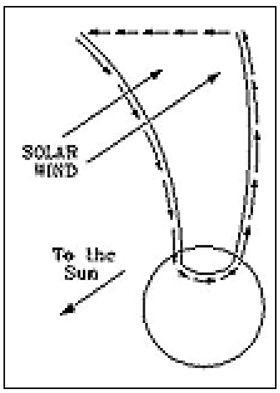
"Any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change is produced, the voltage will be generated. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, rotating the coil relative to the magnet, etc." [xiii]

Birkeland current

The Waterloo Bridge experiment will be a good analogy to explain the Birkeland currents. In 1831 Faraday strung a copper wire along Waterloo Bridge and dipped its two ends into the river separately. As water conducts electricity so a complete circuit is formed. River water is constantly flowing across the magnetic field and therefore there is magnetic flux acting on the flowing water. Although he couldn't measure any current but his idea is proved to be correct.



Waterloo Bridge Experiment [xiv]

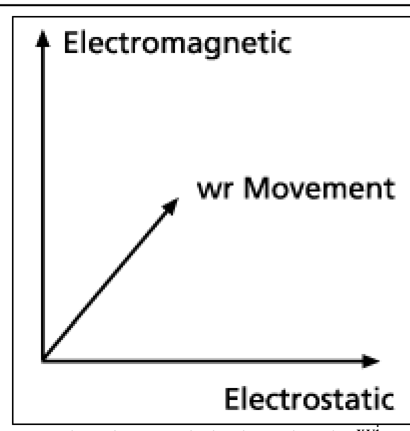


Birkeland's current [xv]

Plasma particles act like conductors in the space and magnetic field lines which are guiding them are just like conducting wires. Electricity can easily pass through the magnetic field lines and they are like the copper wires Faraday used in his experiment. Because of magnetic reconnection the end of the earth's magnetic field lines are joined to the IMF. As the earth's magnetic fields end in the poles so it links the IMF to the polar ionosphere just like Faraday dipped the copper wire into the flowing river. As the solar particles travel across the constant magnetic field just like the flowing water did, a current will be induced according to Faraday's Law. The current passes from the day side magnetic field towards the earth, travels along the ionosphere and passes along the magnetic field in the night side back to the space. However the circuit actually isn't completed because the open ends of the magnetic fields stretch out into the space without rejoining, so strictly speaking the circuit is opened. A possible suggestion is that the open end of the magnetic field is 'bathed' in plasma particles carried by the solar wind and these particles may then complete the circuit.

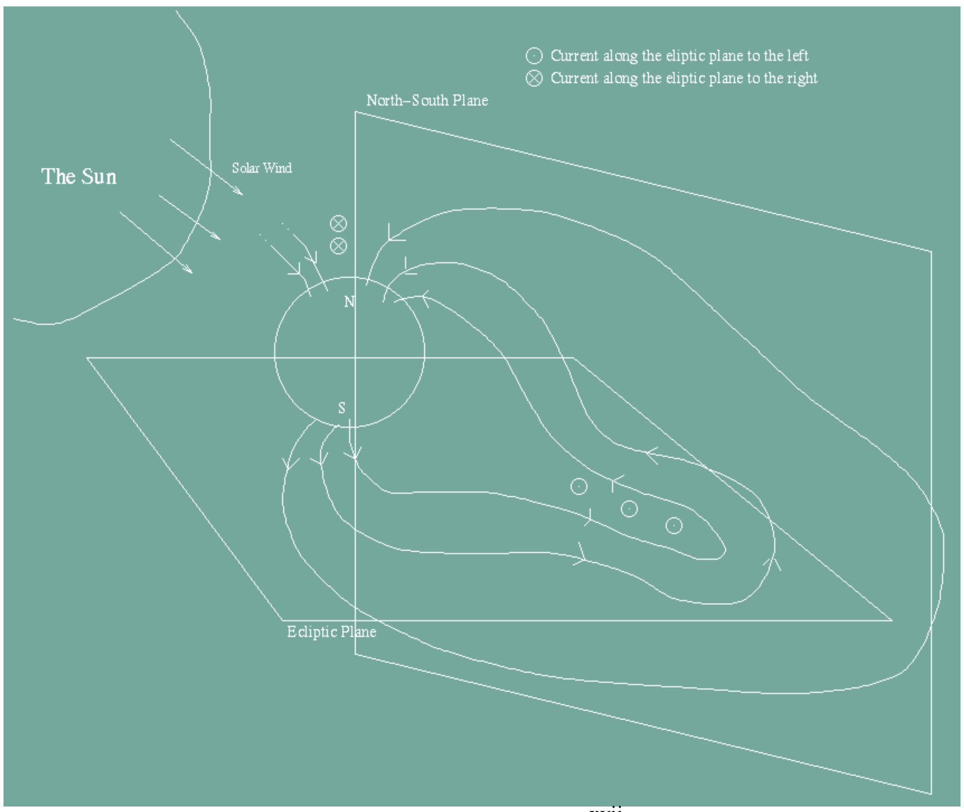
Magnetosperic circulation

Another suggestion about the transverse current above the poles is the convection movement of solar particles in the magnetosphere. Let's first consider the North Pole first. In the North Pole there is a strong downward magnetic field and the solar particles are traveling across it will induce a current. Because of the high conductivity of the plasma particles in the ionosphere, they act like a conductor. The direction of current can be determined by the Fleming's right hand rule. In the illustration below, the current is traveling into the page which means ions will move into the page and electrons will move out of the page since current moves in opposite direction as electrons. The closed



Fleming's right hand rule [xvi]

loops of magnetic fields in the night side continuously stretched outward and away from earth due to the dragging effect of the solar wind. The causes the plasma particles along the field lines traveling with them. As there is an outward flow of particles in the constant magnetic field of magnetosphere, a current will be induced. With reference to the diagram below, there is a current traveling out of the page which is opposite to the transverse current above the poles. Ions and electrons which enter the earth's magnetosphere in the cusps will be directed b the transverse current on the poles and to the magnetotail. They continue around the magnetotail line and reach the poles again where they crash into more particles, generating more charged particles to start the cycle. Therefore there is a continuous influx and outflux of plasma particles in the ionosphere, thus a continuous current above the poles.



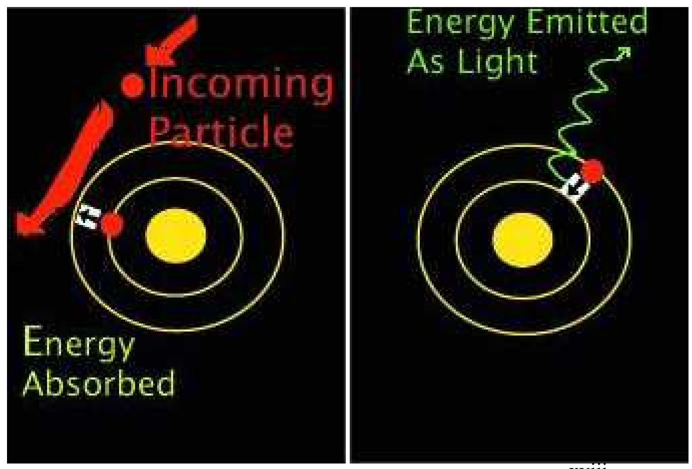
Plasma convection [xvii]

Aurora acceleration region

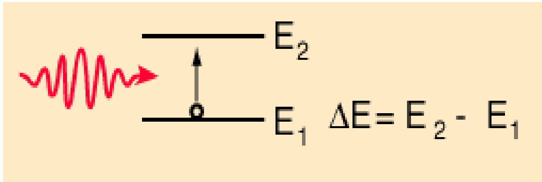
In order to pass through the mirror point where there is a strong repulsing force pushing the charged particles backwards, electrons or ions should have to gain some energy from the environment for them to overcome the repulsion. It has been observed that there is an aurora acceleration region above in the earth where there is a potential drop which pushes particles across the mirror region, so the charged particles can enter the ionosphere and travel with the transverse current above the poles. Experiment has been done to prove the existence of this driving voltage and the voltage is about 5-15,000 volts. This voltage accelerates the solar particles through the bottle-neck of the magnetic bottle in the magnetosphere. One explanation of the potential drop is the converging electrostatic shock which creates a parallel electric field. This creates a current into the space, drawing electrons in the ionosphere as electron travels in the opposite direction of the current. However there is another alternative theory. The angle which solar particle spiral along the magnetic field line is the pitch angle. It is the ratio of $\mathbf{v}_{\mathbf{perp}}$ to $\mathbf{v}_{\mathbf{para}}$. It has been discovered that incoming electron pitch angles are bigger than incoming ion pitch angles which means ions will have a bigger parallel velocity component than the rotational velocity component. So when ions reach the mirror point, they can travel lower in the magnetic mirror points than electrons. There is an accumulation of ions in the lower location than electrons which creates a charge separation with positive charge in the lower part and negative charge in the higher part. This electric field parallel to the magnetic field pulls the electrons towards the earth through the mirror point.

Aurora formation

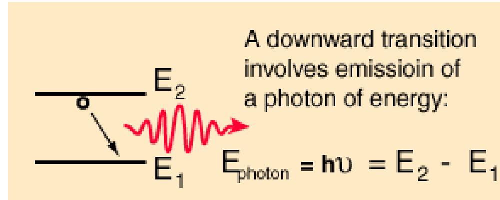
We have discussed all the sub processes which lead to the formation of aurora so what actually is happening in the poles where aurora is seen? Let's follow an electron from the solar wind to see what is happening. The electron travel to the earth along with the solar wind and luckily will enter the earth's distorted magnetosphere. It is then being trapped in the magnetic bottle in the magnetotail where it bounces back and forth in the two mirror points. Part of the solar particles may gain enough energy from the aurora acceleration region and enter the ionosphere by the driving voltage. These solar particles spiral along the magnetic field lines and travel into the lower attitude of the atmosphere where they interact with the plasma particles in the ionosphere. When they travel along the magnetic field and ionosphere, they form a current which pass from the day side to the night side transversely above the poles. Charged particles, in this case electron, bombard with neutral atoms in the earth's atmosphere. When these fast moving electrons bump into the molecules, the electron of the molecules will be removed from its original orbit and 'jump' to a higher energy level. This process is called excitation. Soon the electron which circulates around the outer perimeter of the atoms will 'jump' back to its original lower orbit and give out the excess energy. During the process a photon of light with specific wavelength will be given out depending on the difference in the energy levels. The process is similar to the discharge of a neon lamp. The wavelength of light can be calculated from the Planck constant.



Atomic excitation and light emission [xviii]



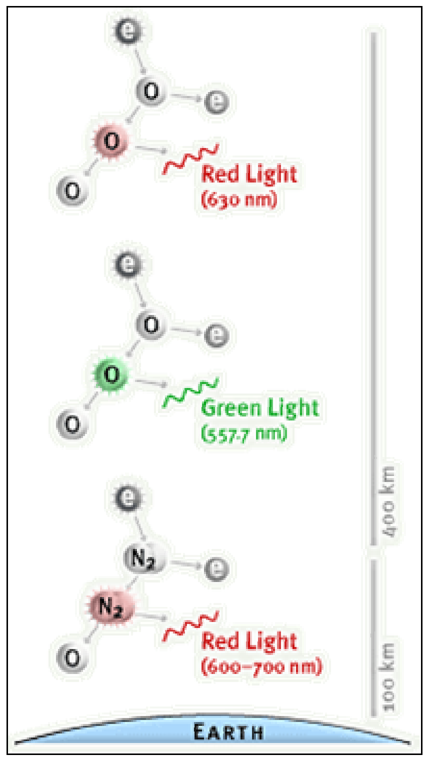
Energy absorption



Light emission [xix]

E_1 and E_2 are the ground state and the excited state of the element respectively. The difference between them is the energy absorbed by the promoted electron (ΔE). When the excited electron 'jumps' back to its ground state it will give out the excess electron which is ΔE and frequency of the light can be calculated through the equation: $\mathbf{E} = \mathbf{h} \times \mathbf{f}$ where **h** is the Planck constant and **f** is the frequency of light. Wavelength of light can be found subsequently by $\mathbf{v} = \mathbf{f} \times \lambda$ which **v** is the speed of light.

Aurora is usually a whitish green light, but it can sometimes be red or even a mixture of colors. This is because there is a mixture of gases in the atmosphere which is dominated by oxygen and nitrogen. Atomic oxygen is responsible for the green and red emission. Nitrogen causes blue and red lights. Different colors of light are found in different altitude because the composition of atmosphere in different height varies, so the light emitted will be different. Various ionosphereic atoms will emit UV light which are not visible on the ground because it is absorbed by the atmosphere. Aurora features can come in different size and shapes depending on the solar activity. Aurora is always present in the poles as luminous oval. It produces a ring in the earth poles because the magnetic field lines converge in a circle in the poles so plasma particles interact along this ring. The curtain of light move every moment because electrons are traveling very quickly as they collide with the plasma particles.



Light emission in different altitudes [xx]

Conclusion

Aurora started as a supernatural mystery. Before it was seen as wonders which human didn't understand, but now it is seen as evidence of nature governed by orderly rules. Aurora still hasn't been fully understood yet, but research is being done. Many theories have been proposed to the formation of potential drop in the aurora acceleration region, but none of them has been proven. Recently research has been done on aurora sounds which seem to associate with aurora formation. These beautiful glows of light in the poles in fact show us the complex interaction between the sun and earth, thus how planets are linked together in the universe.

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The Exploration of the Earth's Magnetosphere. http://www-istp.gsfc.nasa.gov/Education/wmap.html
Learning about Aurora. http://sprg.ssl.berkeley.edu/~cyclopi/lesson1.html
Applied physics laboratory site. http://www.jhuapl.edu/newscenter/pressreleases/1998/auroras.htm
NASA website. http://www-istp.gsfc.nasa.gov/
Web Exhibits site. http://webexhibits.org/
Britannica Online. http://www.britannica.com/
Hyperphysics. http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

Evaluation on resource:

My source information comes from books, journals and internet. The information about most topics is quite consistent except the formation of voltage drop in the aurora acceleration region. There are many theories explaining the phenomenon, but I only concentrated on the two main ones.