PALEO AURORA
about 4 billion years ago

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Abstract

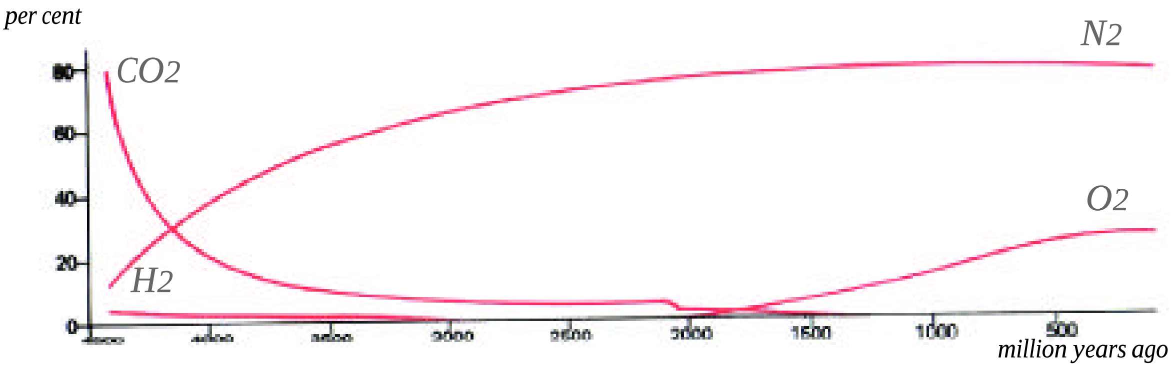
In this thesis it was suggested that a different aurora from the present one had occured on the Earth. The author called it the paleo aurora. The paleo aurora might have occurred on the primitive Earth about 4 billion years ago, when the Earth had an atmosphere dominantly of carbon dioxide. The spectrum of the paleo aurora was expected. Then, it is natural to consider that the spectrum of the paleo aurora and the spectrum of the present aurora should differ from each other because of the difference of the atmospheric compositions. However, there is a possibility that the spectrum of the paleo aurora was almost the same as the spectrum of the present aurora although the atmospheric compositions was completely different from the present one. In addition to the spectrum, other features about the paleo aurora was expected. Then it can be concluded that the paleo aurora had occurred at higher latitudes on average than it does today and that the paleo aurora was more active than it is today. The paleo aurora is a thing of the past. However the paleo aurora may be observed in the extra-solar systems in the foreseeable future.

Contents

1. *Introduction*

It was on the primitive Earth where the paleo aurora might have existed. The present aurora occurs on the present earth surrounded by an atmosphere of molecular nitrogen and oxygen. On the other hand, the paleo aurora might have occurred on the primitive Earth surrounded by an atmosphere of carbon dioxide. According to the study of atmospheric evolution (Walker 1977), There was a time when the Earth had an atmosphere of carbon dioxide. Figure 1 indicates the evolution of the major atmospheric compositions on the Earth.

Figure 1. Evolution of the major atmospheric compositions on the Earth.



The ordinate represents the number ratios of the atmospheric compositions in per cent. The abscissa represents the time in million years ago. This figure was taken from figure 17.1 on page 276 in the book edited by Smith in 1981.

It is considered that carbon dioxide had dominated on the primitive earth. Molecular oxygen emerged into the atmosphere about 2 billion years ago (Cloud 1968; Cloud 1972), that is, about 2.5 billion years later from the birth of the earth. The planets, including the earth, was born about 4.6 billion years ago (pp. 119-123, Hartmann 1993).

The aurora is a swarm of photons from excited atoms or molecules in the polar upper atmosphere. The excited atoms or molecules emit photons as they change their quantum states from upper to lower states. The wavelength of the emitted photon is determined by the energy difference between the upper and lower quantum states of the emitter. Each atom or molecule has its own quantum states. Therefore, the kind of emitter determines the wavelengths of emitted photons. Consequently atmospheric compositions determine the colors of aurora.

The atmospheric compositions have changed, as shown in Figure 1. Thus, it is natural to consider that the colors of aurora have changed. However, the next section implies the possibility that the colors of paleo aurora might have been the same as the present aurora. The following sections address the paleo aurora from some aspects qualitatively.

2. *Atmospheric compositions modified by high-energy photons*

The aurora occurs above about 100 km altitude (p.91 in Störmer 1955). In these altitudes, the atmospheric compositions differ from those at the ground. From about 100 km atomic oxygen gradually dominates with increasing altitude (Nier et al. 1964). Atomic oxygen take a leading part in the auroral colors. Figure 2 shows an aurora, whose colors originate from atomic oxygens in the upper atmosphere.

Figure 2. Colors from atomic oxygen

Red is the photon of wavelength 6300 A or 6364 A from atomic oxygen. Green is the photon of wavelength 5577 A from atomic oxygen. The superposition of red and green in the line of sight produces the yellowish colors, including the yellow, orange and yellowish green.
This image comes from the web site at http://climate.gi.alaska.edu/Curtis/aurora/aurora_00.html

Babcock (1923) measured the wavelength of the green light in aurora and obtained a value of 5577.35 A. After that, McLennan and McLeod (1927) identified the auroral green light as photons from atomic oxygens. Atomic oxygen in the upper atmosphere is produced by the photodissociation of molecular oxygen (Nicolet and Mange 1954).

$$O_2 + h\nu(\lambda \le 2420A) \to O + O$$

A photon of wavelength less than 2420 A can dissociate a molecular oxygen.

High energy photons from the Sun dissociate molecular oxygens into atomic ones. That is, the high energy photons from the sun change the compositions in the upper atmosphere where the aurora occurs.

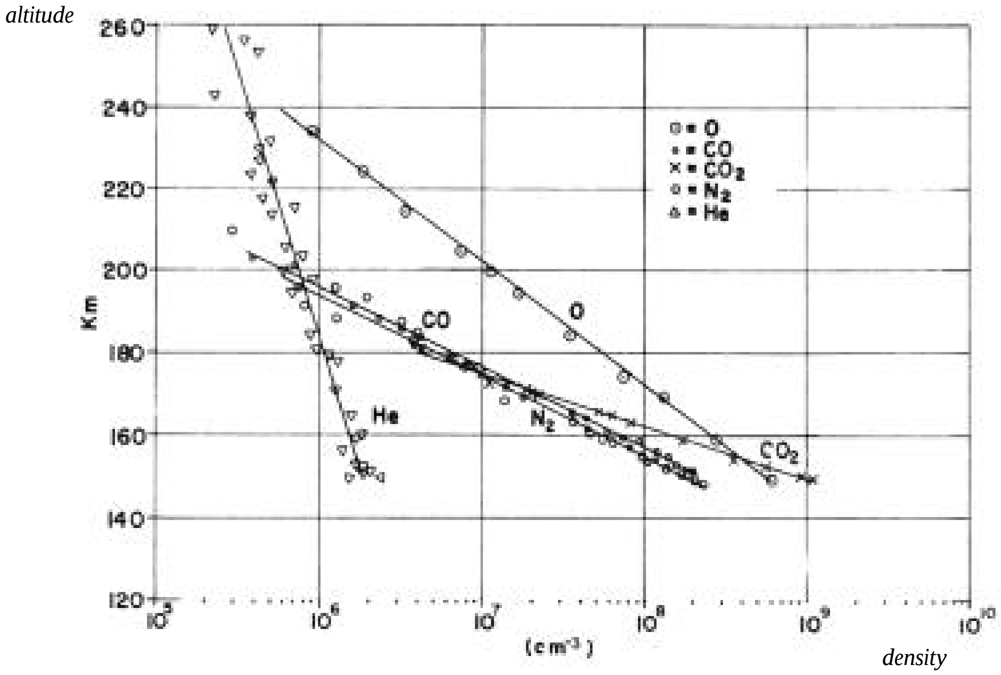
There had been an atmosphere of carbon dioxide on the primitive earth. It is natural that the ancient upper atmosphere was influenced by the high energy photons from the sun. The photodissociation of carbon dioxide might have occurred in the ancient upper atmosphere. The photodissociation of carbon dioxide also occurs at present: It occurs on Venus, which is surrounded by an atmosphere of carbon dioxide. The atmosphere of Venus is composed of carbon dioxide (96.5%), molecular nitrogen (3.5%), and some minor elements (Williams 2001). Before Venus was directly surveyed by satellites, it was suggested that the photodissociation of a carbon dioxide produces a carbon monoxide and an atomic oxygen in the Venusian upper atmosphere (Liu and Donahue 1975; Sze and McElroy 1975):

$$CO_2 + h\nu(\lambda \le 2075A) \to CO + O$$

The photon of wavelength less than 2075 A can dissociate carbon dioxide.

On May 20th, 1978, the Pioneer Venus Orbiter was launched toward Venus. This spacecraft carried 17 experiments, including the neutral mass spectrometer, which observed the neutral compositions in the upper atmosphere of Venus (Niemann et al. 1979 a, b). Figure 3 is one of the results.

Figure 3. Venusian upper atmosphere



The ordinate is the altitude from the Venus' surface in km. The abscissa is the atmospheric density in logarithmic scale. The solid lines represent linear fits to the data points. The negative slope implies that the densities of atmospheric components exponentially decrease with increasing altitude. The rate of the exponential decrease is determined by the scale height, which is dependent on the molecular mass.

Carbon dioxide in the upper atmosphere of Venus is dissociated by the high energy photons, producing carbon monoxide and atomic oxygen. Carbon monoxide is heavier than atomic oxygen. Therefore the scale height of carbon monoxide is smaller than that of atomic oxygen. This produces the difference of slope in the above figure.

This figure was taken from Niemann et al. (1979 a).

High energy photons from the sun destroy carbon dioxides, producing carbon monoxides and atomic oxygens. This phenomena presumably had occurred in the ancient upper atmosphere on the primitive Earth like the present Venus. Therefore it is suggestible that the ancient upper atmosphere of the Earth was dominated by atomic oxygens and carbon monoxides. Then these atoms and molecules might have played a role in paleo aurora.

It is noteworthy that Venus is closer to the Sun than the Earth is. The average distance between Venus and the Sun is about 1.08×10^8 km and the average distance between the Earth and the Sun is about 1.50×10^8 km. Using these values and calculating the energy flux from the sun to these planets, it turns out that Venus receives the high energy photons from the sun by about two times that for the Earth. Therefore the photodissociation on Venus may be more frequent than that on the Earth. However, the ancient Sun might have emitted the intense ultraviolet light and X-ray by 10000 times that of today's sun (Zahnle and Walker 1982). Then, the photodissociation in the ancient upper atmosphere was enough to convert carbon dioxide into carbon monoxide and atomic oxygen significantly. Then atomic oxygen and carbon monoxide should have participated in the spectrum of paleo aurora.

After the photodissociation of carbon dioxide, carbon monoxide and atomic oxygen are produced in the same number. However atomic oxygen is lighter than carbon monoxide. Then the scale height of atomic oxygen is larger than that of carbon monoxide. The scale height is defined by

$$H = \frac{kT}{mg}$$

where k is the Boltzmann constant, T is the temperature, m is the particle mass and g is the gravity constant. Using the scale height, the number density n at the height of z from the reference point can be expressed by

$$n = n_0 \exp\left(-\frac{z}{H}\right)$$

where n_0 is the number density at the reference point. This expression shows that the number density decreases exponentially with increasing height. The rate of decreasing can be measured by the scale height. When the scale height is larger, the rate of decreasing is smaller. Atomic oxygen is lighter than carbon monoxide. Then, the scale height of atomic oxygen is larger than that of carbon monoxide. Therefore, the rate of decreasing of atomic oxygen is smaller than that of carbon monoxide. Consequently, atomic oxygen above the primitive earth should have dominated in higher altitudes. On the other hand, carbon monoxide should have been comparable to atomic oxygen in lower altitudes.

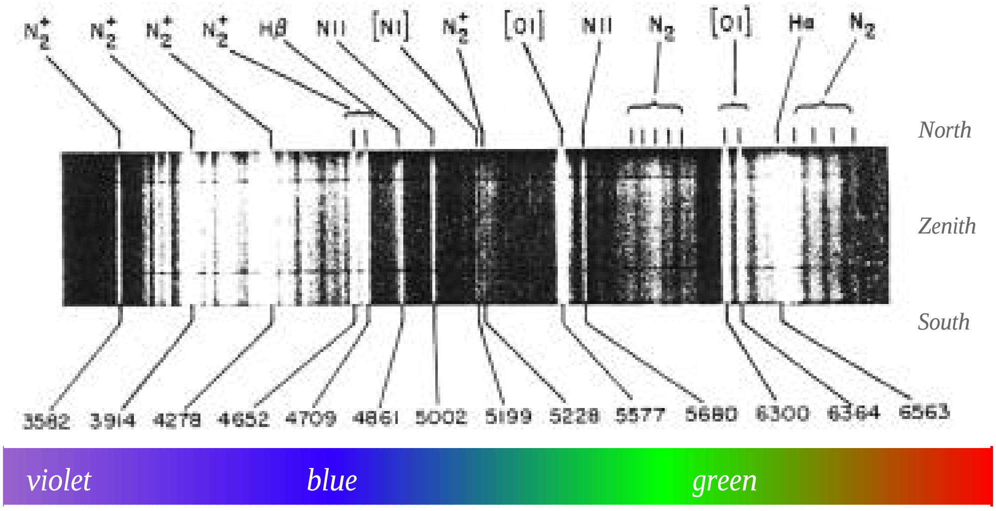
As stated just above, the lighter atomic oxygens can dominate in the higher altitude. On the other hand the heavier carbon monoxides can become comparable to atomic oxygens in the lower altitude. If the auroral particles don't have energies enough to reach the carbon monoxide region, carbon monoxide can't take part in the auroral spectrum significantly. Therefore, the paleo aurora might have been very similar to the present aurora, whose colors are produced dominantly by atomic oxygen. If the auroral particles can reach the carbon monoxide region, carbon monoxides emit the characteristic photons from the lower part of paleo aurora.

On the primitive earth, carbon dioxide had dominated. However the upper atmospheric compositions would have been modified by the high energy photons, which destroy carbon dioxides and produce carbon monoxides and atomic oxygens. These atomic oxygens and carbon monoxides should have been separated by the gravitation. Then atomic oxygen should have dominated in the upper part of the upper atmosphere above the primitive earth. Atomic oxygens presumably had gotten energy from the precipitating particles and had emitted the auroral lights. However it may have been difficult for carbon monoxides to obtain the energy because of the upper atomic oxygen veil. If carbon monoxides obtained the energy, it would have emited the light from the lower part of the paleo aurora. If carbon monoxide did not get the energy, the paleo aurora would have looked like the present aurora although the ground atmosphere was completely different from the present one.

3. *Colors of aurora at present and in the past*

The predominant colors in present aurora and probably in paleo aurora are green and red as shown in Figure 1. These colors are produced by atomic oxygens, which emit the photons of wavelengths 5577 A, 6300 A and 6364 A. In addition to atomic oxygens, neutral and ionized molecular nitrogens also emit visible photons (p.756 in Hallinan 1991). The ionized molecular nitrogen N_2^+ emit photons of wavelengths 3914 A, 4278 A and 4709 A and then produces blue. Neutral molecular nitrogen N_2 produces red by the photons of wavelengths 6500-6900 A. Figure 4 shows the auroral spectrum in the visible region.

Figure 4. Auroral spectrum in visible region



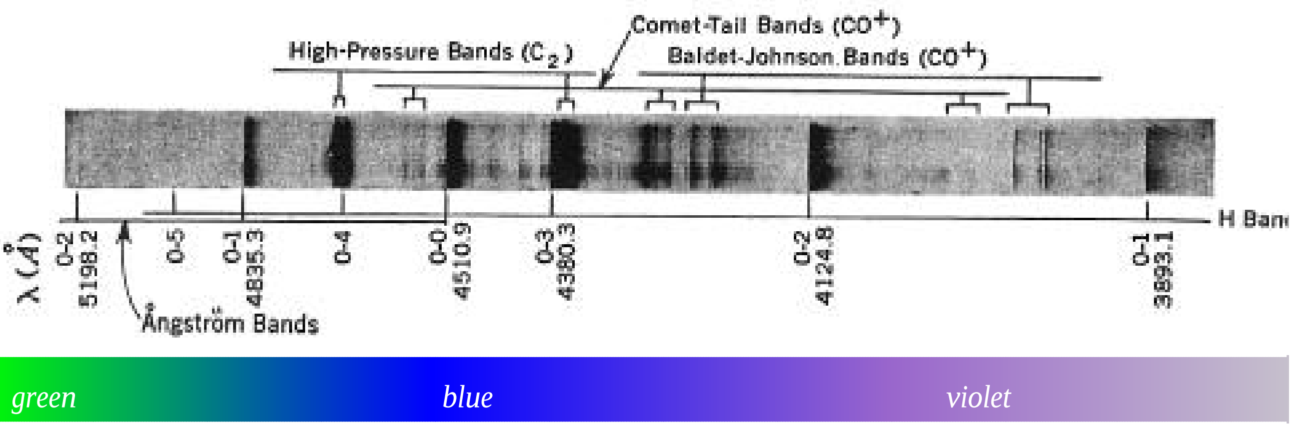
O I stands for neutral atomic oxygen. N I stands for neutral atomic nitrogen. N II stands for ionized atomic nitrogen. H α stands for atomic oxygen's α line in Balmer series. H β stands for atomic oxygen's β line in Balmer series.
The north horizon is at the top, south at the bottom. The horizontal dark lines in the figure are at zenith angles of 45 ° .
Figure 5.1 on page 152 in the book authored by Chamberlain (1961).

Vallance Jones (1971) assembled the auroral spectrum from 1100 A to 17000 A, including the ultraviolet and infrared lights. On the present earth atomic oxygen and molecular nitrogen dominantly produce the colors of aurora. On the primitive earth carbon monoxide might have participated in the spectrum of paleo aurora. And carbon monoxide might have characterized the spectrum of paleo aurora, if it was well supplied with energy.

It should not be ignored that carbon monoxide is a molecule, not an atom. An atom has electric quantum states. On the other hand, a molecule is allowed to have vibrational quantum states and rotational quantum states in addition to electric quantum states. Consequently, the molecule can emit photons of more wide variety of wavelengths than the atom. Therefore it can be expected that carbon monoxide had participated in the spectrum of paleo aurora more widely than atomic oxygen.

The spectrum of carbon monoxide has been studied by a discharge experiment. Figure 5 is one of the results.

Figure 5. Visible spectrum of carbon monoxide

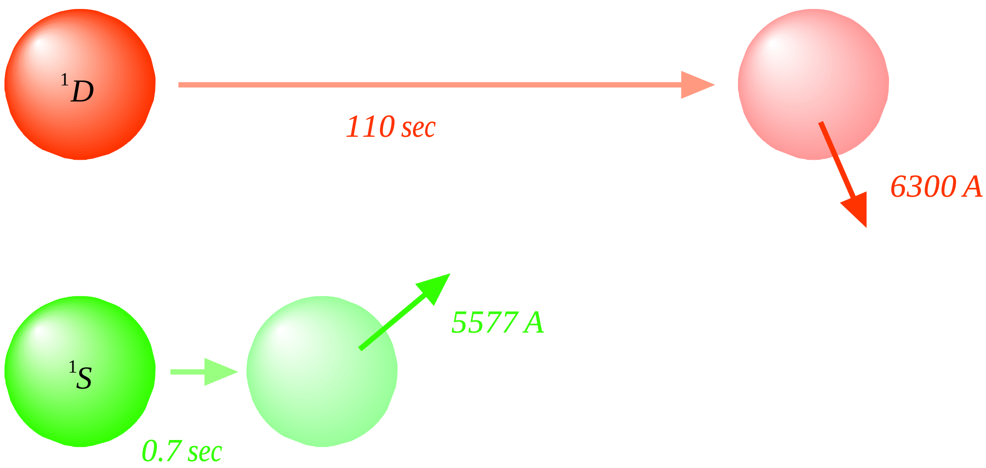


The dark bands in the spectrum show the wavelengths of the light which came from the discharge tube confining carbon monoxide. Most of these wavelengths correspond to the color of blue. C_2 and CO^+ are produced by the chemical reactions on the discharge process.
The spectrum of carbon monoxide was taken from figure 11 on page 35 in the book of Herzberg (1950).

From Figure 5 it may be concluded that carbon monoxides had emitted the blue and violet lights on the paleo aurora. However it should be accepted with caution. Figure 5 shows the light from the gas confined in the discharge tube. The gas molecule often collides with the wall of discharge tube and is deactivated. The deactivated molecule doesn't have the energy for emitting light. Whether the molecule can emit the light or not in the tube is dependent on the mean lifetime of the quantum state. The mean lifetime is the time from the excitation to the radiation of atom or molecule. If the mean lifetime is long the excited molecule will collide with the wall before it emit the light. Thus, excited molecule which has the long mean lifetime can not emit the light in the discharge tube. In the present aurora, the photon of wavelength 6300 A comes from atomic oxygen of the quantum state, which has the mean lifetime of 110 seconds (Omholt 1960). The 6300 A photon from atomic oxygen is not observable in the discharge tube (Hunten and McElroy 1966). However The 6300 A photon from atomic oxygen is the predominant color of aurora. Therefore carbon monoxide in the paleo aurora may also have emitted the photon, which was not observed in the discharge tube.

110 seconds is the mean lifetime of the quantum state ^{1}D of atomic oxygen, which is about to emit the red photon. During the time of 110 seconds, ^{1}D atomic oxygen can move some distances. On the other hand, ^{1}S atomic oxygen, which is about to emit the green photon, can not move significantly. Because the mean lifetime of ^{1}S is 0.75 seconds (Omholt and Harang 1955). Figure 6 shows the schematic diagram about the above discussion.

Figure 6. Excited states of atomic oxygen



The situation indicated by the above figure may give some effects on the auroral morphology. If the wind is blowing hard in the aurora the red aurora may occur at some distances from the green aurora. If the temperature is high in the aurora the red aurora may become vague relative to the green aurora. These phenomena remains to be studied.

The long mean lifetime of ^{1}D atomic oxygen elevates the red (6300 A) aurora region, as follows. In the upper atmosphere ^{1}D atomic oxygen is sometimes deactivated mostly by collisions with molecular nitrogen (Demore and Raper 1964; Hunten and McElroy 1966). If the collision between ^{1}D atomic oxygen and molecular nitrogen is frequent, the red aurora is difficult to be seen. However with increasing altitude the collision becomes scarce. Therefore the red aurora occurs at higher altitudes relative to the green aurora, which is produced by ^{1}S atomic oxygen of the mean lifetime 0.75 seconds. The red (6300 A) aurora occurs above about 200 km altitude. On the other hand, the green (5577 A) aurora occurs above about 100 km altitude.

As stated above, molecular nitrogen deactivates ^1D atomic oxygen, and the red aurora is therefore elevated. On the present Earth molecular nitrogen dominates the atmosphere by about 80%. However on the primitive Earth, molecular nitrogens were not abundant relative to carbon dioxides. Therefore, most of ^1D atomic oxygens on the primitive Earth could have avoided the deactivation by molecular nitrogens. Then it is suggestible that the height difference between the green (5577 A) and red (6300 A) aurora had been smaller than that at present. However carbon monoxide may deactivate ^1D atomic oxygens.

To summarize, the predominant colors of paleo aurora are expected to have been red, green and maybe blue. Red and green come from atomic oxygen. Blue originates from carbon monoxide. Red is located at higher altitudes than green because of the long mean lifetime of ^1D atomic oxygen. Blue is located at lower altitudes than others because of the heaviness of carbon monoxide. Therefore the predominant colors of paleo aurora are red, green and maybe blue in order of altitude. It is difficult for carbon monoxide to obtain energy from the precipitating particles because of the upper atomic oxygen veil. The intensity of red, green and blue is dependent on the intensity of precipitating particles.

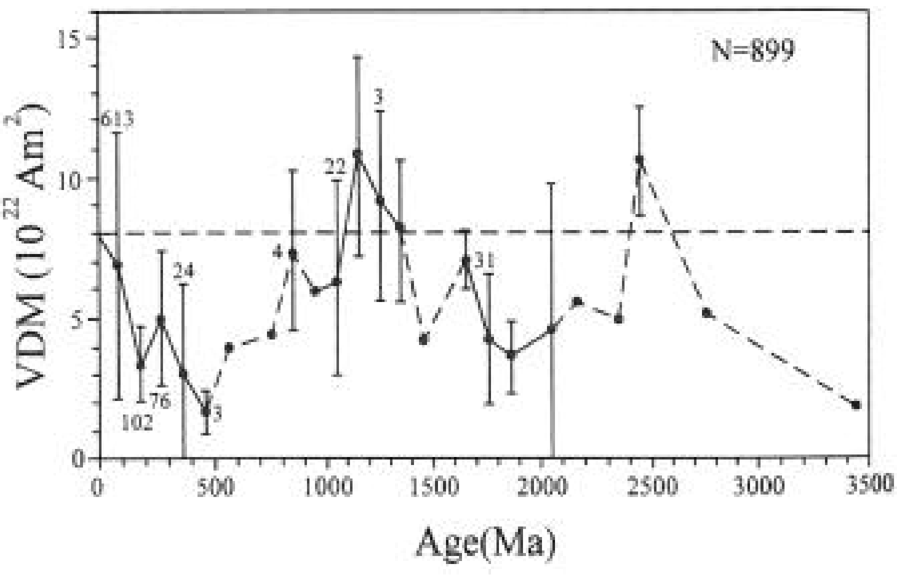
4. Paleo magnetism - necessary for the existence of the paleo aurora

The planet where aurora occurs is not only the Earth. Jupiter and Saturn also have aurora (Bhardwaj and Gladstone 2000). The Earth, Jupiter and Saturn have the same feature. These planets have intrinsic magnetic fields (Russell 1987). Venus and Mars do not have intrinsic magnetic fields (Russell 1987). An aurora has not been observed on Venus and Mars, excluding the paper of Fox and Stewart (1991). It can be concluded that the aurora occurs on the magnetized planets.

The paleo aurora on the primitive Earth needs the intrinsic magnetic field of the primitive earth. If the primitive earth had not have the intrinsic magnetic field, the paleo aurora could not have existed.

The magnetic field in the past days can be deduced from the record of rocks. Figure 7 indicates the deduced dipole moments of the earth from about 3.5 billion years ago up to now.

Figure 7. Geomagnetic field across the Earth's history



VDM is the abbreviation of the virtual dipole moment, which is the calculated dipole moment from the rock record with the assumption that the Earth's dipole field had been axial. N (=899) is the total sample number. The vertical segments are the error bars. The points without the error bars were caluculated from only one sample and then connected by the dashed line to show the unreliability. The horizontal dashed line indicates the value of the present dipole moment. Ma stands for million years ago.

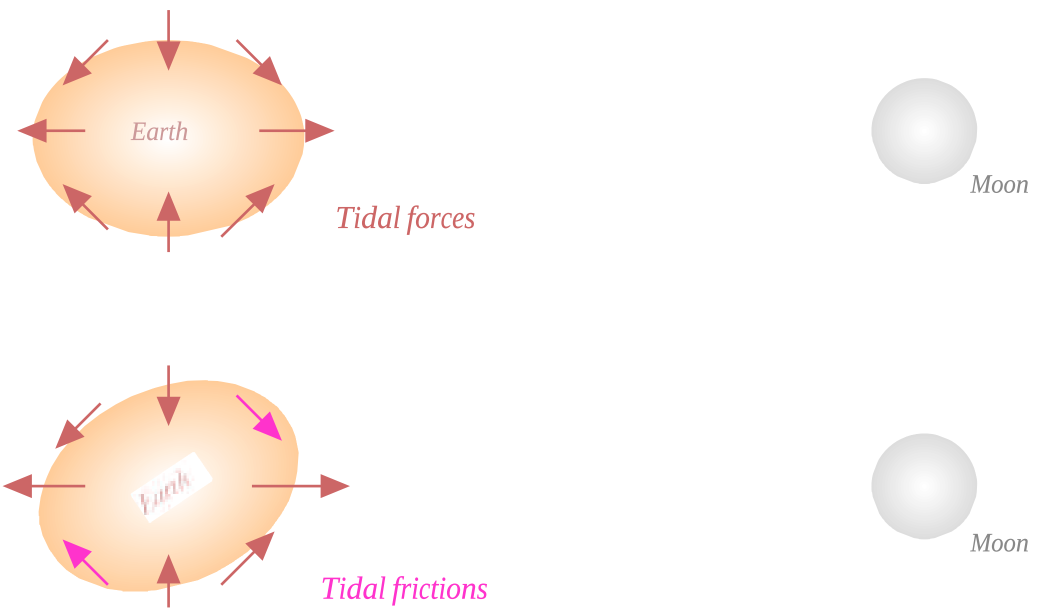
This figure was copied from figure 6.12(b) on page 246 of the book edited by Merrill et al. (1996)

The geomagnetic field is not constant. Sometimes it reverse its polarity. From 5 million years ago until now, the reversal of the geomagnetic polarity occurs 20 times (Fig.5.4, p.170, Merrill et al. 1996). In the history of the Earth, the reversal of the geomagnetic polarity has been frequent. Therefore the magnetic reversal should have occurred sometimes between the measurement points in Figure 7: Some lines connecting points in Figure 7 may be meaningless. In any case Figure 7 indicates that the Earth has had the magnetic field since at least about 3.5 billion years ago. Then the earth has had the aurora since at least about 3.5 billion years ago until now, excluding the magnetic reversal period.

With regard to the primitive Earth about 4 billion years ago, there is no evidence for the geomagnetic field: The rocks born about 4 billion years ago could not survive on the tectonic earth and can not inform the record of the magnetic field of the primitive Earth. However, the magnetic field of the primitive Earth can be approached by the geodynamo theory.

According to the review papers about the theory of the geodynamo (Stevenson 1983; Buffett 2000), the geomagnetic field can exist when the core have the rotation and the convection. It is noteworthy that the rotational rate of the earth is decreasing. Therefore, the primitive earth should have had the rapid rotation. The rotation of the earth has been decelerated by the tidal forces (p.71, Hartmann 1993). Figure 8 shows the mechanism of the deceleration due to the tidal forces.

Figure 8. Tidal forces produced by the moon



The upper panel shows the tidal forces exerting on the Earth which has no-rotation relative to the moon. The tidal foreces make the two bulges on the surface. The lower panel shows the tidal forces exerting on the Earth which has a rotation relative to the moon. The tidal forces make the two bulges on the deviated surface. During the making of bulges, the earth rotates. And then the two bulges are formed on the deviated direction as shown in the lower panel. The tidal forces become the torque to decrease the rate of rotation relative to the moon. The upper panel shows the future earth.

It is little doubt that the rotational rate of the primitive earth had been large. However, the meaning of the rapidness of rotation for the ancient dynamo remains to be studied.

As for the convection in the core, the present convection is promoted by the inner core growth (Stevenson 1983; Buffett 2000). The core of the present earth can be divided into the liquid outer core and the solid inner core. The present core is on the way of the solidification and thus its inner core is enlarging its volume. The solid inner core is composed of pure iron. The liquid outer core is composed of iron and some lighter elements, which is considered to be oxygen and sulfur (Stevenson 1983). When the liquid core change its state into solid, iron in the liquid core become solid and oxygen and sulfur remain liquid. Therefore the remained liquid core become lighter than before and the surrounding before-solidification core liquid. This situation introduce a buoyancy of the remained core liquid. This leads to a convection. Such a convection is called the compositional convection. What's more, when the liquid core become solid one the latent heat emerges. This latent heat also promote the convection.

As the iron in the liquid core become solid, the latent heat is produced. This heat in the core reach the surface someday and can be measured. From the measured heat flux the growth rate of the inner core can be deduced. Laprosse et al. (2001) deduced the inner core growth rate and calculated the birth date of the inner core. According to Laprosse et al. (2001), it is most likely that the inner core was born only 1 billion years ago. This implies that the primitive earth didn't have the solid inner core and its core was totally liquid. It is an inevitable conclusion that the convection in the ancient core would have been promoted by a different mechanism from the present one.

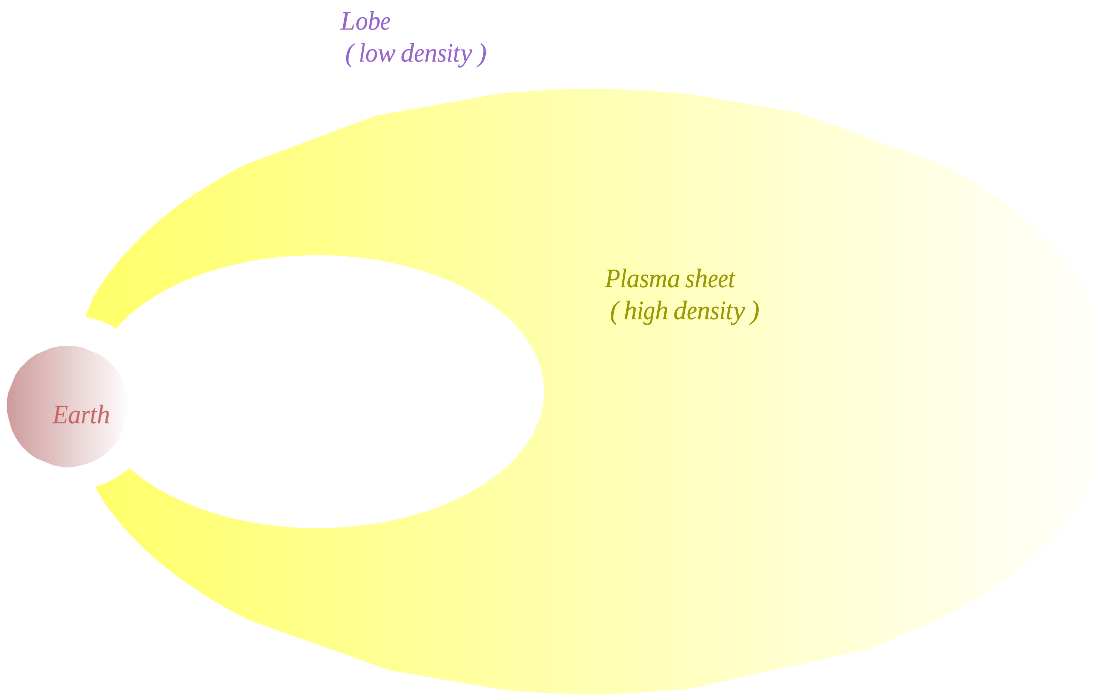
The earth was born about 4.5 billion years ago after the aggregation of some materials. As the materials aggregated, the gravitational energy was converted into the thermal energy. What is more, the radioactive materials produced the thermal energy. The primitive earth presumably was hot due to the these thermal energy and its surface had became cold due to the infrared emission. The center of the earth remained hot and the surface became cold. This is the temperature gradient. If its gradient was sufficient, the convection should have occurred. Then, the geomagnetic field could exist on the primitive Earth. Consequently, the paleo aurora could become suggestible. Stevenson (1983) expected the existence of the geomagnetic field on the primitive Earth with the above mentioned convection mechanism.

To summarize, the paleo aurora needs the intrinsic magnetic field on the primitive Earth. The magnetic field is produced by the dynamo. The dynamo occurs when the core have the rotation and the convection. It is clear that the primitive earth had the rotation. What's more its rotation had been rapid. With regard to the convection in the core, the convection in the primitive Earth's core was different from the present one which is promoted by the inner core growth. The primitive earth didn't have the inner core. Then the core convection mechanism in the primitive earth was different from the present one. The ability of the core convection without the inner core can be supported theoretically by Stevenson (1983) and observably by Figure 7, which indicates the existence of the geomagnetic field about 3.5 billion years ago when the the inner core didn't exist. Then the paleo aurora could exist on the primitive earth.

5. Characteristics of the ancient magnetosphere and the paleo aurora

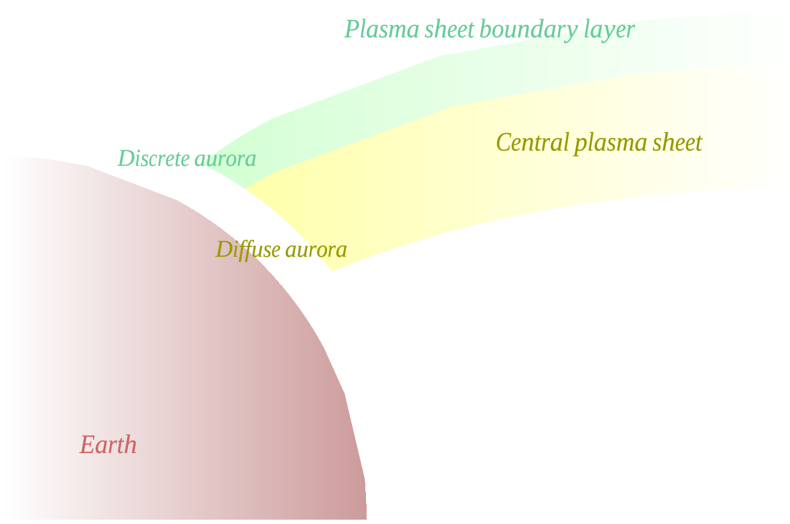
The aurora is a swarm of photons from excited atoms and molecules in the polar upper atmosphere. The atoms and molecules are excited by precipitating charged particles which originate in the magnetosphere. The magnetosphere consists of some characteristic regions, including the plasma sheet. The plasma sheet is characterized by its high density plasma population. The average electron density in the plasma sheet is 0.5 cm^{-3} (p.7, Baumjohann and Treumann 1996). On the other hand, the average electron density in the lobe is 0.01 cm^{-3} (p.7, Baumjohann and Treumann 1996). The lobe and the plasma sheet adjoin as shown in Figure 9.

Figure 9. The locations of the plasma sheet and the lobe



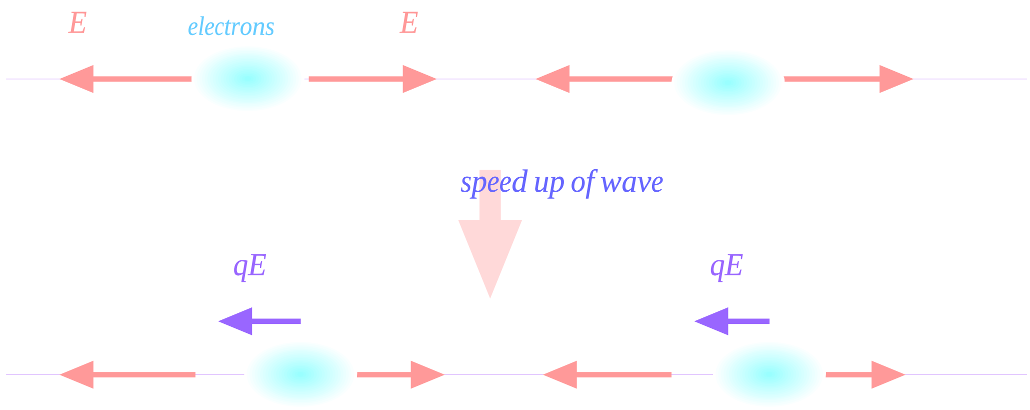
The plasma sheet can be divided into the central plasma sheet and the plasma sheet boundary layer, which faces the lobe (Eastmann et al. 1984). The electron energy distribution in the plasma sheet boundary layer differs from that in the central plasma sheet (Lui et al. 1977). The electron energy distribution in the plasma sheet boundary layer has the trace of an electron acceleration. These accelerated electrons from the plasma sheet boundary layer produce discrete aurora. On the other hand, electrons in the central plasma sheet are not accelerated on the way from the tail plasma sheet to the atmosphere and produce diffuse aurora (Lui et al. 1977). The diffuse aurora occurs at the lower latitudes than the discrete aurora as shown in Figure 10.

Figure 10. Near earth plasma sheet



The discrete aurora is produced by the accelerated electrons from the plasma sheet boundary layer, which face the low density region called the lobe. Therefore the density gradient exist on the plasma sheet boundary layer. According to Hasegawa (1976), MHD surface wave occurs in the place where the density gradient exist, including the plasma sheet boundary layer. And then this MHD surface wave produce the kinetic Alfvén wave by the mode conversion. The kinetic Alfvén wave has a component of its electric field in the direction of the ambient magnetic field. Such a wave can trap the electrons by its parallel electric field (pp.245-255, Chen 1984). The charged particles trapped by the kinetic Alfven wave are transported in the speed equivalent to the phase speed of the kinetic Alfvén wave. As the kinetic Alfvén wave approaches the earth, the phase speed increases and then the trapped particles are accelerated. Figure 11 is the schematic diagram of the trapping and acceleration of the electrons by the kinetic Alfvén wave propagating along the magnetic field line.

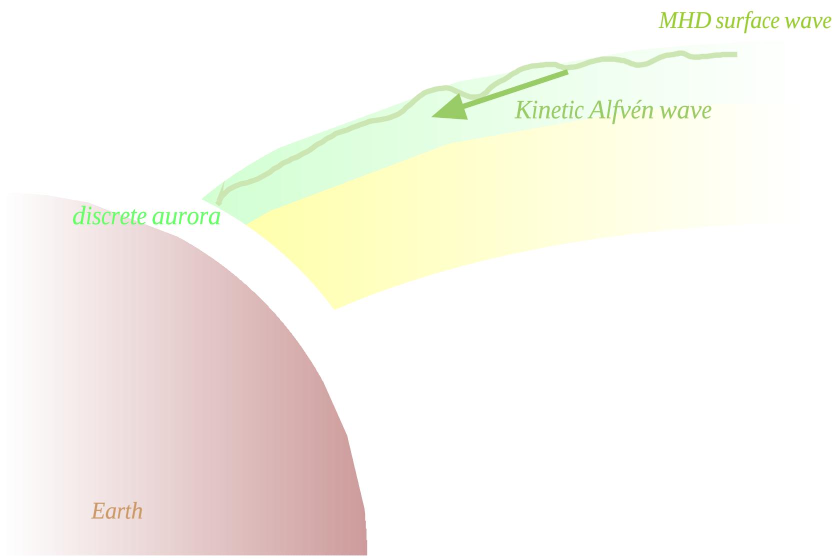
Figure 11. Wave trapping and acceleration



If the speed of wave is close to that of electrons, the wave can trap electrons in the crests of the its electric potential. The electrons have minus charges and tend to oscillate with their distribution center being the crest of the electric potential.
If the wave speeds up, the net force exert on the electrons. The electrons follow the speeding wave. It is worth noting that the wave decreases its energy for accelerating the trapped electrons and damps. The electrons absorb the energy from the speeding wave. If the electrons completely absorb the energy from the wave, the electrons will be independent. However the following wave again trap the accelerated electrons. And the accelerations continue until some ends.

These trapped particles become auroral particles for the discrete aurora. The discrete aurora often has the curtain structure. This curtain structure can be considered to be the manifestation of the MHD surface wave on the plasma sheet (Hasegawa 1976). Figure 12 shows the illustration of this theory.

Figure 12. Hasegawa's theory for the discrete aurora

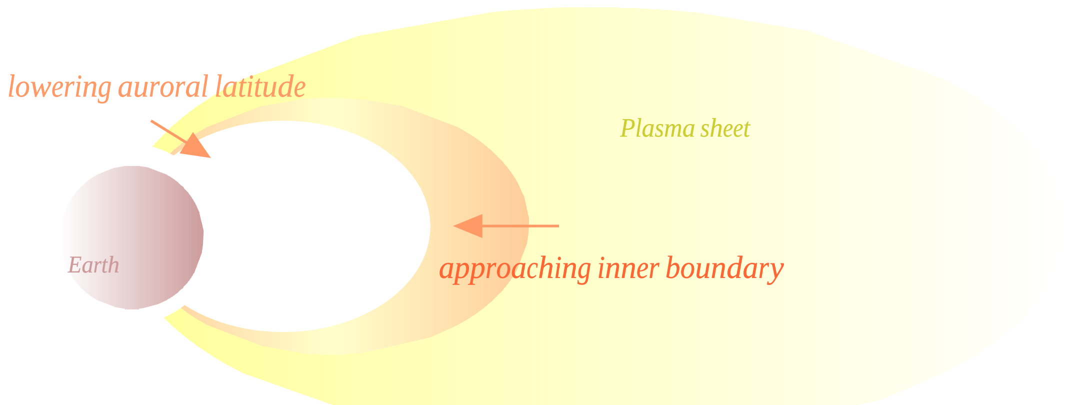


MHD surface wave occurs on the surface of the plasma sheet. MHD surface wave produces the kinetic Alfvén wave, which propagates along the magnetic field. On the way to the Earth, the kinetic Alfvén wave traps the electrons of almost the same speed and accelerates these electrons. The accelerated electrons produce the discrete aurora with curtain structure, which is the manifestation of the MHD surface wave.
MHD surface wave can occur on other regions where the density gradient exists, for example, the plasmapause and the inner boundary of the plasma sheet, if some seed disturbances are supplied.

The phase speed of the kinetic Alfvén wave is nearly proportional to the ambient magnetic field intensity. Therefore, if the Earth has more intense intrinsic magnetic field, the kinetic Alfvén wave change its phase speed more rapidly. Supposing the theory of Hasegawa (1976) is correct, the auroral particles could be accelerated more strongly as they approach the strongly magnetized Earth. If the primitive Earth had the intense magnetic field, the paleo aurora would be more intense than that of today's aurora. It is noteworthy that the Hasegawa's theory is one of the several theories for the electron acceleration (Borovsky 1993).

The night side aurora is located under the footpoints of the magnetic fields embedded in the plasma sheet. Therefore, it is natural that the movement of the plasma sheet displace the night side auroral region. Vasyliunas (1968) observed the equatorial inner boundary of the plasma sheet became closer to the Earth during the magnetically disturbed periods. Winningham et al. (1975) observed that the night side aurora occurred at lower latitudes during the magnetically disturbed periods than the magnetically quiet periods. When the inner boundary of the plasma sheet approaches the Earth, the aurora occurs at lower latitudes. This coincidence of two phenomena is obvious from Figure 13.

Figure13. Approaching inner boundary of plasma sheet



When the inner boundary of the plasma sheet approachs the Earth, the night side aurora can occur at lower latitudes.

These two phenomena can be attributed to the enhanced magnetospheric convection. The magnetospheric convection is the bulk plasma motion in the magnetosphere. The plasma motion include the electric drift and the magnetic drift. The electric drift (E×B drift) is induced by the solar wind and the rotation of the earth. The solar wind produce the electric field expressed by

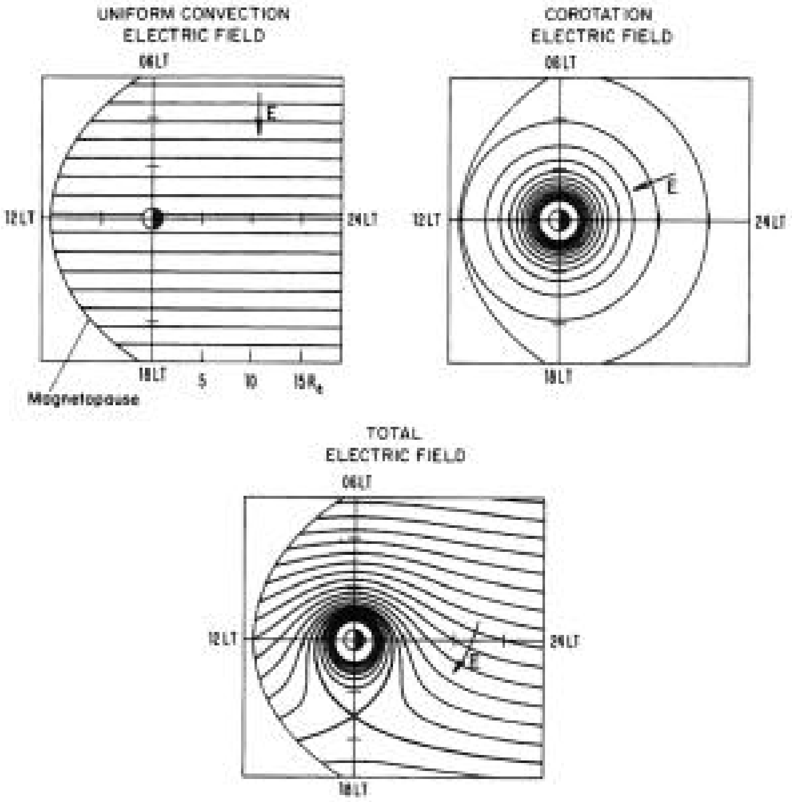
$$E_{sw} = -V_{sw} \times B_{sw}$$

where V_{sw} is the solar wind speed and B_{sw} is the interplanetary magnetic filed embedded in the solar wind. When this electric field enters into the magnetosphere, it produces the sunward plasma motion in the magnetosphere. However, the electric field induced by the solar wind is smaller than the rotational electric filed in the vicinity of the Earth. The rotational electric field is produced by the rotation of the Earth and expressed by

$$E_{rotation} = -(\omega \times r) \times B_{geo}$$

where ω is the angular velocity of the terrestrial rotation, r is the geocentric distance and B_{geo} is the geomagnetic field. Figure 14 shows the stream lines of the plasma electric drift induced by the solar wind and the terrestrial rotation.

Figure 14. Magnetospheric convection on the equatorial plane



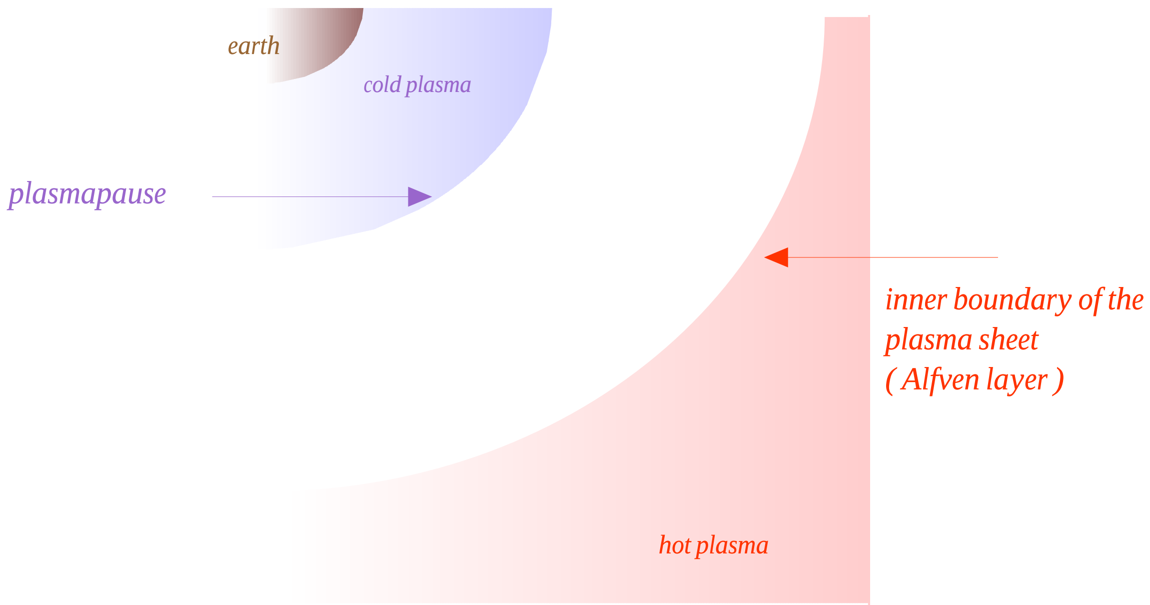
The upper left panel indicates the stream lines of plasmdrifting under the electric field induced by the solar wind. If the solar wind has the magnetic field of southward component, the sunward flow occurs in the magneosphere. The upper right panel indicates the stream lines of plasmdrifting under the electric field induced by the terrestrial rotation. The lower panel is the superposition of the upper two. The terrestrial rotation bend the plasma streamline induced by the solar wind and keep the plasma away from the earth. If the Earth's rotation is more rapid, the plasma from the tail will be kept further away from the Earth. The primitive Earth had a rapid rotation.
This figure descends from the book of Parks (1991).

In addition to the electric drift, the magnetic drift also contributes to the bulk motion in the magnetosphere (Kavanagh et al. 1968). The magnetic drift is expressed by

$$v_B = (2W_{//} + W\ )\frac{B\times\ \ B}{q|B|^3}$$

where $W_{//}$ is the parallel component of the particle energy to the ambient magnetic field, W is perpendicular component. q represents the charge of the particle. The magnetic drift is dependent on the particle energy. On the other hand, the electric drift is not dependent on the particle energy. For low energy particles, the magnetic drift is negligible. Thus, the bulk motion of the low energy plasma can be approximated by the electric drift as shown in Figure 14. It can be seen that the closed stream lines exist near the Earth. The Earth is the source of the low energy plasma, which occupy the closed stream lines and make the high density region, that is, the plasmasphere (Kavanagh et al. 1968). For high energy plasma, the bulk motion is modified by the magnetic drift. The bulk motion of the high energy plasma is the superposition of the electric drift and the magnetic drift. The direction of the magnetic drift is dependent on the sign of charge. The direction for the electron is the same as the electric drift induced by the rotation of the earth. It is clear from Figure 14 that the rotational electric drift bend the stream line of the plasma coming from the magnetospheric tail to dawnward. The magnetic drift for the high energy electron also bend the stream line to dawnward. For high energy electrons, the magnetic drift expand the forbidden region in the equatorial plane. For low energy plasma, the forbidden region is correspond to the plasmapause. For high energy electron, the forbidden region is correspond to the inner boundary of the plasma sheet (Kavanagh et al. 1968). The average electron temperature of the plasma sheet is 5,000,000 K. On the other hand, the electron temperature of the plasmasphere is 5,000 K (Baumjohann and Treumann 1996). Figure 15 shows the forbidden regions of the hot and cold electrons.

Figure 15. Forbidden regions for the hot and cold electrons



The primitive Earth had a rapid rotation, which intensify the corotation electric field in the magnetosphere. This intense corotation electric field expand the forbidden region for the cold and hot electrons. Then the plasmasphere of the primitive earth might have been larger than it is now. In addition, the inner boundary of the plasma sheet might have been located farther from the Earth than it is now. The distant inner boundary of the plasma sheet means that the magnetic field embedded in the plasma sheet have the footpoints at relatively high latitude. Therefore, the paleo aurora might have occurred at higher latitudes on average than the present aurora.

Vasyliunas (1968) observed the equatorial inner boundary of the plasma sheet became closer to the earth during magnetically disturbed periods. It can be explained by the enhanced magnetospheric convection. When the solar wind speed is high, or the southward component of the interplanetary magnetic field is large, or both, the convectional electric field becomes large and promotes the sunward motion of the plasma in the magnetosphere. Then the forbidden region become closer to the earth than usual. That is, on the enhanced magnetospheric convection, The tail plasma goes over the preceding inner boundary of the plasma sheet and becomes closer to the earth than before. Vasyliunas (1968) observed the forbidden region of the relatively high energy electrons, not protons. Protons has the forbidden region closer to the Earth than electrons (Kavanagh et al 1968; Chen 1970), because the magnetic drift of the positive charge particles is antiparallel to the corotational electric drift. The positively charged particles can approach the Earth, drifting from the night side to the dusk side. These positively charged particles constitute a ring current, which induce the magnetic field on the Earth and disturb the geomagnetic field in low latitudes. With an enhanced magnetospheric convection due to the intensification of the solar wind speed and/or the southward component of the interplanetary magnetic field, the positively charged particles reach closer to the Earth, inducing a larger magnetic disturbance in the low latitude regions. In addition, the forbidden region boundary of electrons become closer to the Earth.

The ring current is composed of the protons and atomic oxygens (Nosé et al. 2001). The atomic oxygens in the ring current presumably were born in the auroral ionosphere of the Earth. It is possible that the primitive Earth sent out carbon monoxides in addition to atomic oxygens and then the ancient magnetosphere was contaminated with carbon monoxide.

6. Relation between the Young Sun and the paleo aurora

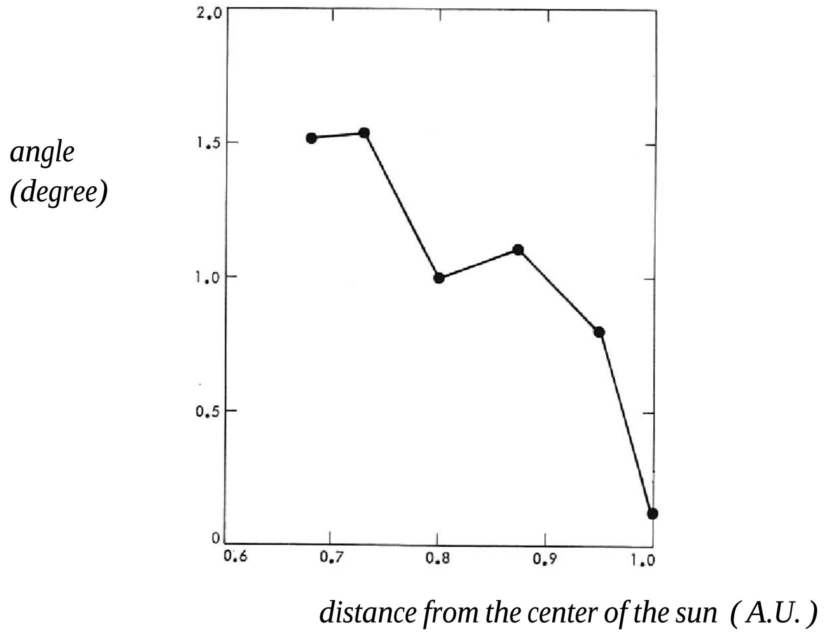
From the Sun the solar wind flows out. The Earth is bathed in the solar wind. The solar wind interacts with the magnetosphere and influences the aurora by some way. The aurora is produced by the auroral particles, which precipitate into the polar upper atmosphere and supply the energy for the aurora. The precipitation rate of the auroral particles is strongly dependent on the solar wind parameters, including the speed, magnetic field strength and direction (Liou et al. 1998).

The paleo aurora should have been influenced by the ancient solar wind from the ancient Sun. In order to speculate the features of paleo aurora, the study of the ancient Sun is inevitable. Studying the ancient sun may sound difficult. However, it should be noticed that the Sun is one of the stars. The stars can be seen in the night sky and it is no doubt that there are a lot. The stars live their lives in the broad universe. Some stars are young, and others are old. The ancient Sun belongs to the young stars and they share the same features. The ancient Sun can be studied by observing the young stars in space.

The ancient Sun has already been studied. The review paper of Zahnle and Walker (1982) reported that the ancient Sun had a rapid rotation and emitted the intense ultraviolet light, X-ray and the intense solar wind. I think that the rapid rotation is responsible for the intensification of the ultraviolet light, X-ray and solar wind. It is considered that the rapid rotation intensify the dynamo action and produce the strong magnetic field (Johns-Krull et al. 2000). The magnetic field is considered to do an important role for the coronal heating (Priest 1995; Dwivedi and Phillips 2001). I think that the strongly heated corona emit the ultraviolet light, X-ray, and the solar wind intensely.

The ancient Sun rotated more rapidly than it does today. The Sun has decreased its rotational rate. There is a theory that the sun has decreased its rotational rate by means of the solar wind, which has the angular momentum and thus extracts it from the Sun (Weber and Davis 1967). This theory has been confirmed by the observations of the angular momentum in the solar wind (Neugebauer 1975; Richardson et al. 1996): Figure 16 shows the angles between the radial and azimuthal components of the solar wind velocity observed by Mariner 5, which shows that the solar wind has the angular momentum extracted from the Sun.

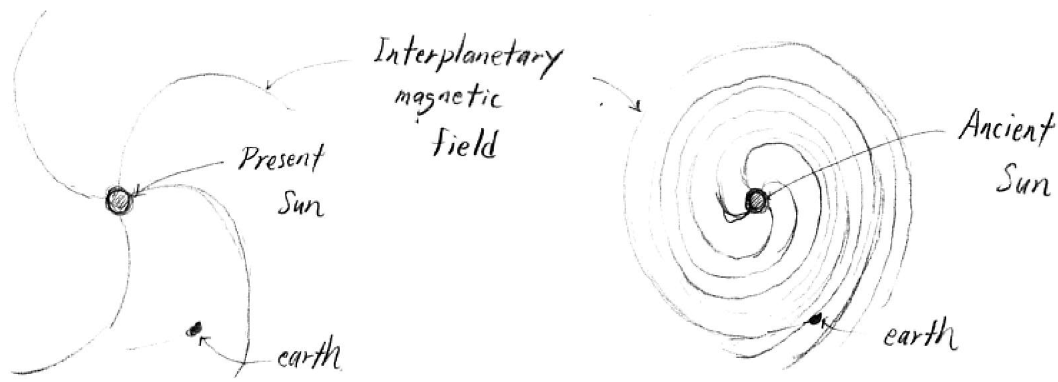
Figure16. Angles between the azimuthal and radial velocity components.



On June 14 in 1967, Mariner 5 was launched toward Venus, which is about 0.7 AU from the solar center. On the way Mariner 5 measured the solar wind velocities. The points in the above figure is the 27 days average values. The magnitude of the angular momentum per mass can be obtained by the multiplication of the heliocentric distance and the azimuthal speed of the solar wind. I f the angular momentum is constant in the solar wind, the azimuthal speed of the solar wind decreases with increasing distance from the sun's center. This situation is manifested in the above figure, which was taken from Neugebauer (1975).

From the above, there is no doubt that the ancient Sun had a rapid rotation. The rapidness of the solar rotation would influence the configuration of the interplanetary magnetic field. Figure 17 shows the present and the expected ancient configurations of the interplanetary magnetic fields on the ecliptic plane.

Figure 17. Ancient interplanetary magnetic field



The curved lines are the interplanetary magnetic field embedded in the solar wind. The curved lines are not the streamlines of the solar wind, which is nearly radial. The left figure shows the present interplanetary magnetic field anchored to the slowly rotating sun. The right figure shows the ancient interplanetary magnetic field anchored to the rapidly rotating sun.

The source of the interplanetary magnetic field is the magnetic field on the sun (Parker 1958; Isenberg 1991). As the solar wind expand radially, the sun rotates, pulling around the magnetic field connected to the expanding solar wind. Consequently, the interplanetary magnetic field become spiral. The interplanetary magnetic field anchored to the rapidly rotating sun would be more sharply spiral.

The mathematical representation of the interplanetary magnetic field, with some idealizations, is as follows (Isenberg 1991):

$$B_r(r,\theta,\psi) = B(r_0,\theta_0,\psi_0)(r_0/r)^2$$
$$B_\psi(r,\theta,\psi) = -B(r_0,\theta_0,\psi_0)r_0^2\Omega\sin\theta/rV$$
$$B_\theta(r,\theta,\psi) = 0$$

which are represented in the heliocentric spherical coordinates (r,θ,ψ). The quantities with subscript 0 represent the quantities at the sun's surface. Ω is the angular velocity of the rotation of the sun. V is the solar wind speed. It is clear that if the magnetic field on the Sun : $B(r_0,\theta_0,\psi_0)$ is intense, the interplanetary magnetic field is also intense. The ancient sun presumably had the intense magnetic field due to the active dynamo promoted by the rapid rotation. Then it can be said that the ancient interplanetary magnetic field was more intense than it is now. Then the paleo aurora might have been more active than the present aurora.

7. Paleo aurora on Mars

Mars do not have an intrinsic magnetic field at present (Russell 1987). However, there is the possibility that Mars had an intrinsic magnetic field in the past: The Mars Global Surveyor spacecraft detected the magnetic field from the Martian rocks (Connerney et al. 2001). The detected magnetic field may be one recorded by the Martian rocks in the past, when Mars had an intrinsic magnetic field and the Martian paleo aurora.

National Aeronautics and Space Administration (NASA) has a plan to bring Martian rocks to the Earth in the near future (Savage 2000). If it is realized, the time can be deduced by the radioactive methods. The time is when Mars had an intrinsic magnetic field and a Martian paleo aurora.

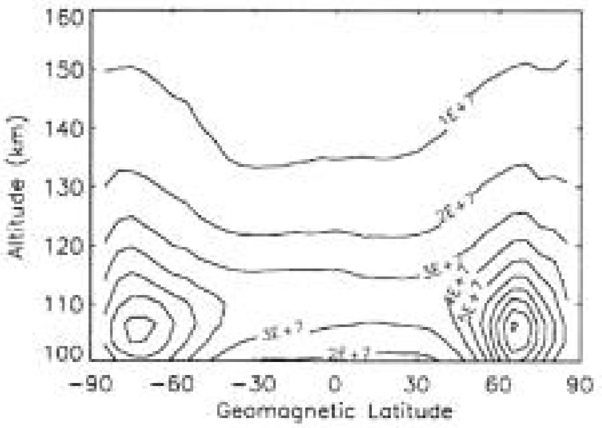
The present atmosphere of Mars is composed dominantly of carbon dioxide: The present atmospheric compositions of Mars are carbon dioxide (95.32%), molecular nitrogen (2.7%), argon (1.6%), and some minor elements (Williams 2001). The ancient atmosphere of Mars remains to be studied.

8. Auroral products on the present Earth and Jupiter

After the bombardment of auroral particles the polar upper atmosphere gains their energies, some of which are converted into the radiant energy to produce aurora. It is also known that the energies are used to promote the chemical reactions in the auroral region. The chemical reactions in the auroral region produce new chemical compositions, as stated below.

In the auroral region of the present Earth nitric oxide is produced (Solomon et al 1999). Figure 18 shows the average nitric oxide density in the upper atmosphere.

Figure18. Average nitric oxide densities

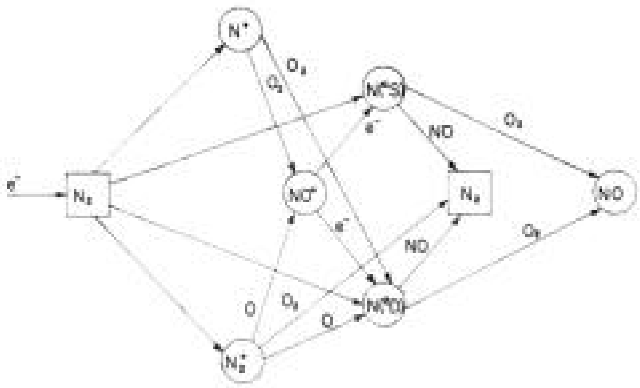


The density values are in cm^{-3}. This figure was taken from Solomon et al. (1996).

Figure 19 shows the chemical reactions to produce nitric oxide after the collision between the energetic electron and molecular nitrogen.

Figure19. Formation of nitric oxide

This figure originates from the paper of Hyman et al. (1976)



Nitric oxide has an intriguing feature. Nitric oxide can destroy ozone after the following chemical reaction:

$$NO + O_3 \rightarrow NO_2 + O_2$$

Nitric oxide produced in the aurora may contribute to destroy the ozone layer (Solomon 1982). That is, there is a possibility of some relations between the aurora and the ozone hole. However, the ozone hole is the phenomenon which occurs almost only in the southern hemisphere in October. October in the southern hemisphere means the spring, when the temperature begins to increase. Then the polar stratospheric clouds disappear (Solomon et al 1986): The polar stratospheric clouds may acquire an invisible gas state in October. Then, these liberated gases destroy the ozone layer and produce the ozone hole. During winter the polar upper atmosphere become cold. Then the downward flow occurs. The downward flow transport the nitric oxide produced by the aurora into lower atmosphere, where the polar stratospheric clouds come into being. I think that the auroral nitric oxide may be absorbed in the polar stratospheric clouds and liberated on October to destroy the ozone.

In the auroral region of Jupiter hydrocarbons (C_2H_2, C_2H_4, C_3H_3 and so on) and benzene are produced (Bhardwaj and Gladstone 2000; Wong et al. 2000). Figure 20 shows the Jovian aurora and the polar haze, which is considered to be composed of the hydrocarbons.

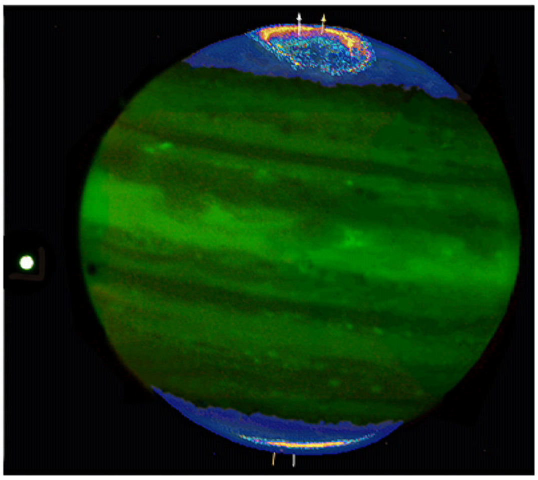


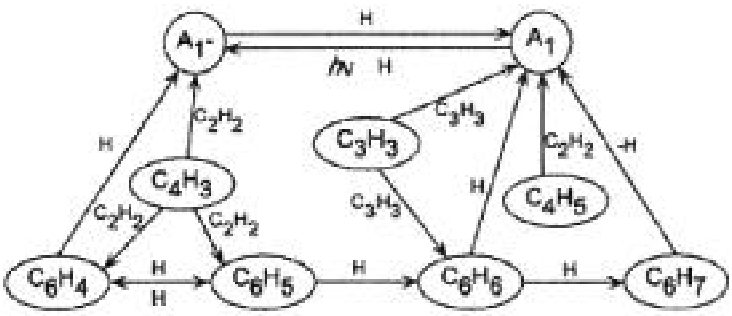
Figure 20. Jovian aurora and its products.

The infrared emission from Jupiter was observed by the ISAAC instrument on the ESO Very Large Telescope at the Paranal Observatory in Chile. The observation was carried out on November 14, 2000, when Jupiter was 610 million km from the Earth. The yellow and orange show the Jovian aurora. The blue color shows the polar haze, which is considered to be the hydrocarbons produced by the auroral particles. The small circle seen at left is Io.
This image originates from the web site at http://www.hq.eso.org/outreach/press-rel/pr-2001/phot-21-01.html

Figure 21 shows some pathways of the chemical reactions in the Jovian aurora.

Figure 21. Chemical reactions in the Jovian aurora

A_1 is benzene. This figure originates from the paper of Wong et al.(2000).



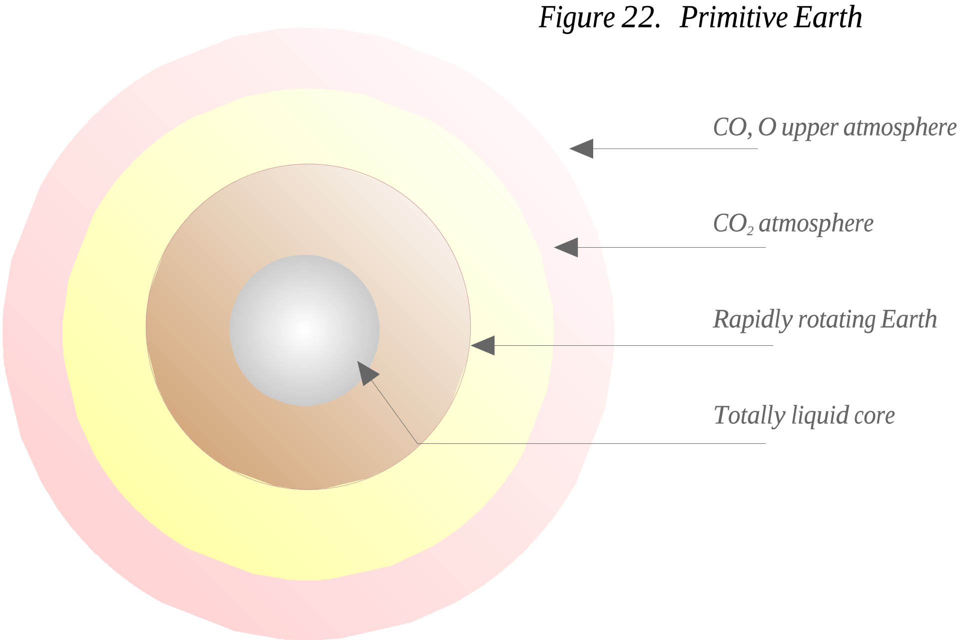
It is no doubt that the aurora is the place where some chemical reactions occur and something is produced. It is clear that the chemical reactions and their products in the aurora are characterized by the atmospheric compositions.

The atmosphere on the Earth has evolved. The life changed the atmosphere on the Earth (Walker 1977). The life obtain the energy from the Sun by means of the photosynthesis. The photosynthesis consume carbon dioxide and produce molecular oxygen. The oldest fossils are about 3.5 billion years old and they inform that the life had already utilized the oxygen-producing photosynthesis (Schopf 1993; Schopf 1999). The life oxygenated the earth's atmosphere. Therefore, it is natural that the following theory was born. Molecular oxygen in the atmosphere is the sign of life (Schindler and Kastling 2000). If the planets outside the solar system emit the light from molecular oxygen in the atmosphere, its observation will be an evidence of the extraterrestrial life (E.T.). Ozone is also the sign of life, because ozone is produced from molecular oxygen. The Terrestrial Planet Finder will be able to observe the sign of life from the extraterrestrial planet in the near future. Terrestrial Planet Finder will be launched between 2012-2015. The information about this mission is available from the web site at http://tpf.jpl.nasa.gov/. The aurora on the extrasolar planets will be also observable someday, not excluding the paleo aurora. However what I want to see is not only the light of the paleo aurora, but also the light behind the paleo aurora, because it can be allowed to think that the paleo aurora produce some ingredients for the origin of life.

9. *Summary*

The paleo aurora was discussed qualitatively in this thesis. The paleo aurora might have occurred on the primitive Earth. The primitive Earth was characterized by the rapid rotation, the totally liquid core, and the atmosphere dominantly of carbon dioxide, as shown in Figure 22.

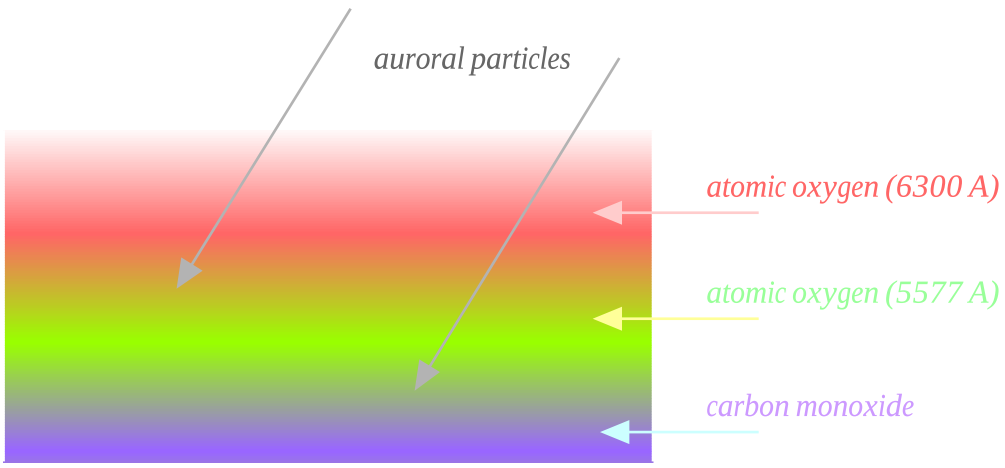
Figure 22. Primitive Earth



The Earth was born with the thermal energy. On the way of the refrigeration, the Earth's surface became cold, while the Earth's center remained hot. This situation introduced the temperature gradient inside the primitive Earth and led to the convection in the totally liquid core. Then, the geomagnetic field emerged from the primitive Earth and constructed the ancient magnetosphere. In the ancient magnetosphere, the bulk plasma motion was determined mostly by the electric drift and the magnetic drift. The electric drift can be divided into the corotational electric drift and the solar wind-induced electric field. The corotational electric drift in the past was intense because of the rapid rotation of the primitive earth. The solar wind-induced electric field was also intense when the interplanetary magnetic field had the parallel component relative to the earth's dipole moment. Because the magnitude of the interplanetary magnetic field was presumably intense. Consequently, the bulk plasma motion in the ancient atmosphere should have been more active than it is today.

From the active ancient magnetosphere, the auroral particles presumably had precipitated into the upper atmosphere of the primitive earth. The upper atmosphere of the primitive earth should have been influenced by the intense ultraviolet light and X-ray from the young Sun. The intense ultraviolet light and X-ray presumably dissociated a carbon dioxide into a carbon monoxide and an atomic oxygen. Then, atomic oxygens had dominated the upper part of the ancient upper atmosphere due to their lightness relative to carbon monoxides, which was comparable to atomic oxygens in the lower part of the ancient upper atmosphere. The precipitating particles coming from the ancient magnetosphere energized atomic oxygens preferentially. Thus, atomic oxygens could get the sufficient energies and should have emitted photons in the paleo aurora. Atomic oxygen could emit photons of wavelengths 5577 A (green), 6300 A (red), and 6364 A (red). On the other hand, it was difficult for carbon monoxides to obtain the sufficient energies from the precipitating particles, whose energies had already consumed by atomic oxygens above. If the precipitating particles left the energies for carbon monoxides, carbon monoxides maybe emitted photons of wavelengths corresponding to the blue and violet colors. Figure 23 shows the tentative colors of paleo aurora.

Figure 23. Rainbow colors of paleo aurora



Red was located at higher altitudes than green because of the long mean lifetime of ^1D atomic oxygen. Blue was located at lower altitudes than others because of the heaviness of carbon monoxide. Consequently, the paleo aurora might have looked like the rainbow in colors. However, there needs more quantitative works to estimate the colors of paleo aurora. Figure 23 shows the tentative colors of paleo aurora.

The paleo aurora should have influenced by the ancient solar wind from the young Sun as shown in Figure 24.

Figure 24. Youths of the Sun and the Earth

The solar wind from the young sun presumably had an interplanetary magnetic field which differed from the present one because of the rapid rotation and the strong magnetic field of the young Sun. The rapid rotation of the young Sun sharpened the spiral structure of the interplanetary magnetic field as shown in Figure 17. The strong magnetic field of the young Sun intensified the magnitude of the interplanetary magnetic field. The intensified interplanetary magnetic field maybe enhanced the magnetospheric convection. This led the active paleo aurora, from which carbon monoxides and atomic oxygens flowed out. Then, the ancient magnetosphere might have been contaminated with carbon monoxides in addition to atomic oxygens.

The paleo aurora might also have occurred on Mars, whose rocks recorded the intrinsic magnetic field of the ancient Mars. Venus might have had an aurora, or will have, or have, or never.

The auroral region is the place where some chemical reactions occur and something is produced. Nitric oxide is produced in the present aurora on the Earth. The hydrocarbons are produced in the Jovian aurora. What was produced in the paleo aurora on the primitive Earth remains to be studied.

--. *Future aurora*

Following the NASA's mission : Terrestrial Planet Finder, the European Space Agency will launch a spacecraft named Darwin. The information about the Darwin mission is available from the web site at http://astro.estec.esa.nl/IRSI/. These missions will search the terrestrial planets outside the solar system. The extrasolar terrestrial planets must also have the aurora. Then, the paleo aurora may be observed. What is more, the future aurora may be observed. The future missions may reveal the beginning of life. In addition, the future missions may reveal the end of life. The future aurora remains to be studied.

10. *Acknowledgement*

I wish to express my heartfelt thanks to the following people. First of all, I appreciate the supervision of Professor Kiyohumi Yumoto, who permitted me to pursue this study. I could study this theme almost freely. Secondly, I am most grateful to Associate Professor Hideaki Kawano for his lecture and criticism. Dr. Kawano gave a lecture to the senior undergraduate student on the magnetospheric plasma physics. I derived a good deal of benefit from his lecture. In addition, Dr. Kawano criticized my written English, including this thesis. Then, I could improve my English-writing skill. Thirdly, I would like to add my thanks to the members of Space and Earth Electromagnetism Laboratory. They kindly helped me by some way and gave me a comfortable feeling. I was happy being a member of Earth Electromagnetism Laboratory. Fourthly, I must appreciate the financial support from my parents, who paid the university fees and gave me a living allowance every months. With their support, I could study at Kyushu university and write this thesis. Last but not least, I would like to appreciate the works of great people. I sometimes noticed that I was on the wrong direction during my research. However, I learned that there are some directive hints for the research in the works of great people. I made reference to the works of great people in this thesis. The following pages are filled with the great names and works.

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