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Effects of high-speed protons of solar wind on the ionosphere of the Earth

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Abstract When an charged particle is exercising, it accompanies with magnetism. When the velocity of the charged particle become zero, the magnetism is lost. The protons (H^+) of the solar wind combines by a magnetic field made by exercising at ultra-high speed, and the magnetic field separates H^+ and the free electron. At more than 150km above the Earth, H^+ of the solar wind create ionospheres of F layers. Formation of E and D layers are supported by ionization of atoms such as oxygen by X-ray or ultraviolet rays. There is the peak of hydrogen atomic density at the intermediate altitude between the E-layer and the D-layer. The sporadic E that is generated in the bottom of E layer is thought to be due to the H^+ group of solar wind.

Keywords Solar wind, Proton, Larmor radius, Magnetic storm, Ionosphere, Sporadic E-layer, Plasma bubble

1. Introduction

It is said that the ionosphere is formed by irradiation of protons (H^+), ultraviolet rays or high-energy electrons those come from the Sun, but there is no detailed discussion about the effects of protons. [1].

The solar-winded protons reach the Earth at a high speed of about 450km/sec, of which kinetic energy is about 1.06 KeV. The protons move along the magnetic field lines in the Earth's magnetosphere, where free electrons are produced by the collision ding atoms and molecules in the atmosphere, and these electrons contribute to formation of the ionospheres.

Although D-layer (at altitude 60km~90km) exist only during the day time and do not exist at night, F layer (150km～800km) and E layer(100～120km) s exist all day [2]. Therefore, it has been considered that, the ionosphere of D layer was formed by ionization of the atmosphere by ultraviolet rays and X-rays from the Sun. It is considered that the formation of the upper ionosphere was affected by the collision of the protons with the atmosphere. The explanation is based on the fact that the lifetime of proton in solar wind is long.

The author will point out that there is a magnetic coupling among charged particles with the same velocity. That is, the magnetic coupling caused by high speed charged particles has a characteristic to align the same type of charged particles. The magnetic coupling is opposite to the coulomb force, and the electron that moves together with proton is separated magnetically.

There is a magnetic reconnection theory as a theory that plasma is heated even on the surface of the Sun [3],[4]. The traditional theory explained that an acceleration of plasma was occurred when horizontally across magnetic field lines are converted together to a new magnetic field. Those theory do not include how magnetic field lines are formed.

Some of protons released from the Sun at ultra-high speed were captured by the Earth's magnetosphere, and formed Van Allen belt. The outer belt is located at an altitude of 10,000 - 20,000 km, has a lot of electrons, and the inner belt is located at 2,000 - 5,000 km and has a lot of protons. There are ionospheres in lower space than the Van Allen belt.

The protons from the Sun collide with molecules in the Earth's atmosphere and it generates free electrons in upper layered ionospheres. As an exceptional example, the lowest ionosphere D-layer disappears in night hemisphere. That is, the free electrons in D-layer are generated by ionization of oxygen atoms due to ultraviolet rays from the Sun.

There is the theory that the daily fluctuations on the propagation of radio waves are affected by interactions between the atmosphere of the Earth [5]. But in this paper, it will be described that the fluctuations on the ionosphere are depended on the protons of the solar wind.

Sporadic E propagation (E_s) enables very high frequency (VHF) radio signals to travel over much greater distances and it is often generated in the time of day and evening [6]. The E_s layer is generated in the lower E-region at altitudes of approx. 90 to 160 km, and the maximum electron density of E_s layer is 9.5×10^5 cm^{-3} at an altitude of 98 km. It was confirmed that protons reach the Earth at the time of magnetic storms, because the region with a high ratio of (N_2/O) extended from the polar region to the mid-latitude and low latitudes [7]. This article will explain that E_s layer occurs by the group of protons those are deeply invaded via the solar wind.

As another phenomenon, there occurs the plasma bubble that is the area with low electron density in ionosphere appears at around sunset in the equatorial region and the structure that is extended at direction along north and south moves to the east [8]. There is a theory that plasma bubbles involve gravitational waves caused by convection activity in tropical atmospheres [9]. However, A large group of protons will be formed intermittently, because the higher speed solar wind that is caused from the stronger microflare captures the lower speed solar winds during the solar wind propagates to the Earth. The plasma bubbles can be understood as the effect of large wave of protons.

In order to estimate the life time of proton in the ionosphere, it was assumed that the boundary of altitude was 150km where percentage of protons decreased and the particles of the Earth's atmosphere increased based on the data of CIRA 1972 by COSPAR [2]. When the atomic density of the atmosphere at an altitude of 150km is converted into the number of molecules, it is $2.4\text{x}10^{10}$ [pieces/(cm^3)]. The amounts of protons (i.e.10^9 kg/sec) from the Sun that reach the cross-sectional area of three times the radius of the Earth is $1.9\text{x}10^9$ [pieces/(sec・cm^2)]. According to above mentioned assumption, the number of protons is at an altitude of 150 km, the life of the proton will be 24/1.9=13 seconds.

The free mean path of the earth's atmospheric pressure (760Torr) of the air molecules is less than 0.1μm, and the protons of the solar wind collide with the molecules in the atmosphere and reach little to the ground. However, the large momentum of protons in the solar wind is possible to explain origin of the west wind and trade wind, etc [10].

2. Acceleration of protons in the surface of the Sun

2.1. The magnetic coupling among high-speed protons

The gravitational energy of the Sun is given by the formation of the Sun. The pressure becomes very high in the center the Sun, resulting in a high energy state, and it makes possible to take place the fusion of hydrogen atoms.

Since a high-speed-moving proton acts as a current, it has a magnetism. When the protons move in the same direction with high-speed, the proton will bunch by the magnetic coupling of the protons. But, if the electron moves together with the proton, it receives repulsive force by the magnetism of the proton. Although the free electron with a negative charge and a small mass does not affect the momentum of protons, the magnetic coupling affects large effects on the protons in the solar wind.

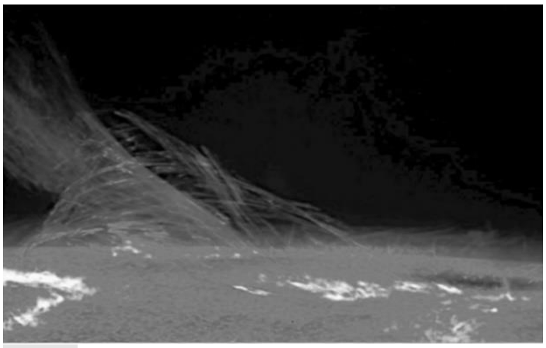

Fig.1. The release of the proton group from the Sun.
Photographed by Hinode's Solar Optical Telescope
https://www.nasa.gov/mission_pages/hinode/solar_017.html

As shown in Fig.1, magnetically linked high-speed protons are released from the surface of the Sun. The magnetic field line that is generated by vertically emitted protons from the Sun is parallel to the Sun's surface. So, the high-speed proton that moves horizontally along the magnetic field line on the surface also occurs. Another proton group which is released from the inside of the Sun to the outside pushes up the horizontally linked protons, and the linked protons becomes a bow. The bow of the protons is released from the surface before long.

The protons and the free electrons those run in the same direction are magnetically repulsive and do not combine soon. The speed of proton becomes large via effects of the rearrangement caused by the magnetic coupling of protons in the corona area of the Sun.

2.2. Amounts of protons captured in the Earth

Van Allen belt is the dense area of charged particles that is formed by magnetic field of the Earth and it exists from 1000km to a range of about three times the earth radius.

The geomagnetic field of the Earth on the daytime hemisphere is compressed by the solar wind, and the magnetosphere of the night hemisphere is stretched away from the Earth by magnetic coupling with protons those come from the solar wind.

Since the rotation of the Sun and that of the Earth are counterclockwise, and the both rotations induce the magnetism with the same direction, the solar wind with the magnetism tends to couple with the magnetism of the Earth. The charged particles incorporate into the ionosphere through the dense magnetic flux around Arctic and Antarctic regions.

The typical value on the amounts of protons emitted from the Sun is $M_{Sun}=10^9$ kg/sec. This value is used to estimate the total amount of protons those will be captured in the Earth.

The total amount of protons captured in the Earth ($M_{Earth\,Max}$) is assumed to the protons captured in the outer Van Allen belt. The cross-section of the outer belt is about nine times the cross-section of the Earth. And the distance to the Earth from the Sun is $1.5\text{x}10^8$ km. By using the ratio on the cross-section of the outer belt for the surface of sphere of $1.5\text{x}10^8$ km radius we get the value of $M_{Earth\,Max}$.

$$M_{Earth\,Max}=M_{Sun}\cdot(9\cdot S_{Earth}/S_{sphere})=4.07\text{kg/sec} \qquad (1)$$

The value of Eq.(2) is converted to the density value.

$$M_{Earth\,Max\,(m^2)}=4.07/\{\pi(6.378\text{x}10^6)^2\}=0.32\text{x}10^{-13}[\text{kg/(sec}\cdot\text{m}^2)] \qquad (2)$$

If this mass is divided by one proton mass and converted into the number of protons per 1cm^2 (N_{Earth}), it becomes an equation (3).

$$N_{Earth\,(cm^2)}=1.9\text{x}10^9\ [\text{pieces/(cm}^2\cdot\text{sec)}] \qquad (3)$$

On the other hand, the boundary altitude where percentage of protons increases more than the molecular density of the atmosphere is more than about 150km as shown in Fig 2, and the molecular density at the boundary is $M_{(150km)}$ $=10^{-9}$kg/m^3=10^{-15}kg/cm^3. Assuming the molecular weight of the atmosphere is 25, the value of $M_{(150km)}$ is converted into number of atoms.

$$M_{(150km)}/m_{\ molecule}=2.4\times10^{10}\ [\text{pieces}/(\text{cm}^3)] \quad (4)$$

It is calculated that protons of Eq.3 have a life time of 13 seconds to reach the amount of Eq.4.

As shown in Fig. 3, the number of protons and molecules present in the upper layer is larger than the electron density.

By using the value of each second by Eq.1, the amounts of protons reaching the Earth on each day is 352 tons/day. The amount of momentum of protons transferred to the molecule in the atmosphere and gives the movement of the atmosphere of the Earth, and the proton of the solar wind obtains electrons and becomes a hydrogen atom.

2.3. Behavior of proton in geomagnetic field

The magnetic force between two paralleling currents is escribed as follows. Assuming the current of I_A [A] and I_B [A] flow in the same direction, respectively, the magnetic field created by conductor A is $H_A = I_A/2\pi d$, and the force (F_m) that parallel conductor B receives from the magnetic field H_A is $F_m = \mu_0 I_B H_A$. Here, d is the distance between current A and current B.

The force that acts between charged particles that move parallel is $F_m = \mu_0 I_B (I_A/2\pi d)$. Since the current (I) is I=qv when charge q is moving at speed (v), the force of $F_m = \mu_0(qv)^2/(2\pi d)$ works to parallel motion of protons away by distance d[m].

On the other hand, the coulomb repulsion force (F_c) between protons at the distance d is $F_c = (q)^2/d^2$. Assuming that the speed of proton is v=900 [km/sec], the distance d* where the coulomb repulsion force is equal to magnetic attractive force is determined by $\mu_0(qv)^2/(2\pi d^*) = (q)^2/d^{*2}$. The value of d* is obtained by substituting μ_0= $4\pi\times10^{-7}$ [H/m].

$$d^*=2\pi/(\mu_0 v^2)=0.5/10^{-7}\text{x}(81\text{x}10^{10})=6.2\text{x}10^{-6}[\text{m}] \quad (5)$$

At the longer distance than d*, the magnetic coupling force among high speed parallelized protons is stronger than the coulomb force between proton and electron in plasma states. F layer exists in the night hemisphere. The phenomenon can be explained by long lifetime of protons those are captured in the magnetosphere. The radius of cyclotron circle of a charged particle in the magnetic field (Larmor radius or gyration radius) is given by equation (6).

$$\text{Larmor radius;} \quad r_{la} = mv/qB \quad (6)$$

Larmor radius is proportional to the velocity of the charged particle. Assuming that, the geomagnetic flux density is B =4.6x10^{-5} [T], the speed of the proton in the field is v=450km/sec, the value of the Larmor radius is given by Eq. (7). Here, the charge on the proton (q) is q=1.6x10^{-19} [C], the mass (m_p) is m_p = 1.67x10^{-27} [kg].

$$r_{la} = (1.67\text{x}10^{-27}\text{x}4.5\text{x}10^5)/(1.6\text{x}10^{-19}\text{x}4.6\text{x}10^{-5}) \fallingdotseq 100\,[\text{m}] \quad (7)$$

On the other hand, the mean free path (λ) is inversely proportional to atmospheric pressure $p_{(Pa)}$. The value of λ in the air is given at λ=0.68/$p_{(Pa)}$ [cm] at room temperature (T=300K). The mean free path at $10^3 p_{(hPa)}$ on the ground is λ_{0m}=6.8x10^{-5}mm=6.8x10^{-2}μm<0.1μm. The pressure at the altitude 200km is $10^{-6}p_{(hPa)}$, the mean free path becomes λ_{200km}=68[m].

3. Effect of solar wind on the ionizing layer

3.1. Mechanism of formation of the ionosphere

The protons are released from the Sun and some of those protons are captured by the Earth's magnetosphere. Those protons propagate along the magnetic field line, and collided with atoms in the atmosphere. The layer of high electron density is generated and reflects radio waves. Although the life span of electrons in plasma is short, the ultrahigh speed protons of solar-wind contributing to the formation of the upper layered ionosphere.

Radio wave of medium band propagates to the range where the terrestrial wave reaches in the daytime hemisphere. But in the night hemisphere, comes to reach from hundreds of to more than 1000km, because the D layer disappears and the medium radio wave is reflected by E layer. E layer at attitude 100km ~150km exists even at night. That is, the protons move around the night sphere of the Earth also and collide with atmospheric molecules. The difference on the ionosphere between day and night indicates that the ionization of ionosphere caused by not only electromagnetic waves but also protons from the Sun.

The electron density of the ionizing layer is more in the daytime hemisphere than in the night hemisphere, and in summer, there is more than winter. The difference of the electron density on the E-layer between day and night is greater than the F layer.

There is F layer at attitude 150km-800km. At the daytime hemisphere, F layer is divided to F1 layer at altitude of 150 km-220km and F2 layer at altitude 200 km to 800km. Short-waves pass through D layer, and those waves are reflected by the F layer with high electron density Radio waves with higher frequencies than VHF or UHF passes through the ionizing layer.

Fig.2 shows altitude dependence of electron density, hydrogen atom density, molecular weight, ozone density, and temperature of Earth's atmosphere.

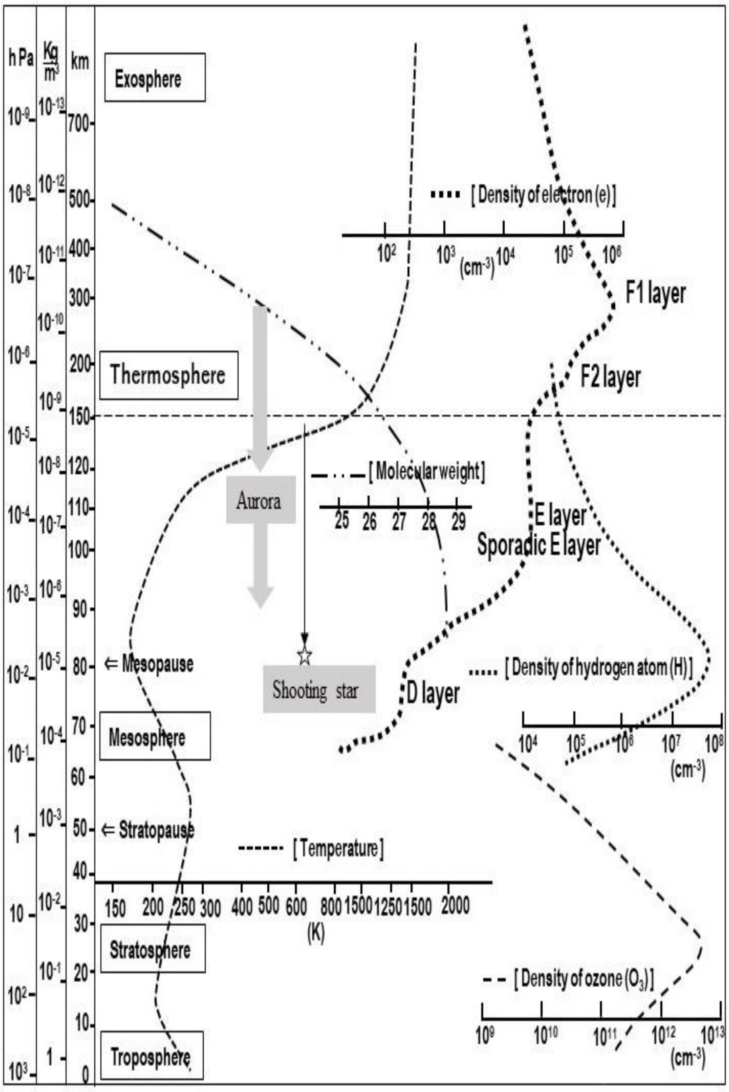

Fig.2. Altitude dependence of electron density, hydrogen atom density, molecular weight, ozone density, and temperature of Earth's atmosphere. Reproduced from [2] https://www.rikanenpyo.jp/kaisetsu/kisyo/ img/kisyo006.jpg

3. 2. Effects of magnetic storm on the ionosphere

When a large flare is released at the Sun, the strong electromagnetic wave is arrived to the Earth after 8 minutes. Then, a sudden ionospherric disturbance (SID) is known as the Dillinger effect takes place [11], [12].

At the Dillinger effect, the free electrons in D-layer reflects the short radio waves (3MHz-30MHz) those are used for of long-distance communication. This sudden failure of propagation of short radio waves occurs in low latitude regions during the day time. The Dillinger effect does not occur at night. It is the evidence that Dillinger effect is caused by X-rays from the Sun. The hard X-rays (wavelengths <1 nm) ionizes atmospheric molecules in D layer i.e. the lowest ionosphere.

The sporadic E layer a special ionizing layer that occurs in the sporadic locally around 100km in the sky in the daytime [6]. Since the electron density of the E-spot is extremely high, the ionizing layer reflects the radio wave of VHF band. The plasma region of E-spot is generated by ionization by the solar wind that invades deeply owing to very high-speed protons.

There is a peak in the density of hydrogen atoms near the interface between the E and D layers, as shown in Fig.2. Why the density of the hydrogen atom peaks exists in the lower layer than the altitude where oxygen atoms and the nitrogen atoms exist. It can be explained as the invaded protons of the solar wind turned to hydrogen atoms.

There is the negative phase storm of ionospheric layer where density of electrons decreases. There is the theory that it is caused by the composition change of the upper atmosphere by the energy of the magnetic storm [13]. But, the main component of the charged particles of a magnetic storm is H^+. The positive ion of H^+ comes from the Sun, and it is able to decrease the electron density of the ionic layer.

The plasma bubble is the phenomenon that the electron density of the ionosphere decreases, and this area extends in the north and south and the occurrence moves to east one after another at around sunset in the equatorial region [8]. This phenomenon is explained as follows. Micro-flares are always occurred and released from the Sun. Since the released velocity of large flare is higher than that of the micro-flares, the slower small flares are absorbed in the large flare. The solar wind of large flare form large cluster. So, the wave of large cluster of protons causes the plasma bubble.

Auroras is the phenomenon that emits light due to the collisions of charged particles in the upper sky and observed at around latitudes of 60 to 70 degrees in the Arctic and Antarctic. At altitudes of 200 km or more, the oxygen atom is ionized and it generates light at a wavelength of 557.7 nm and it looks green or green-white.

At a lower altitude of about 100 km above the ground, which is the lower end of the aurora, density of nitrogen is more than oxygen, so it generates red and blue light below 585.4 nm of nitrogen atoms.

4. Structure of upper atmosphere

4. 1. Altitude dependency of density of atoms

Fig.3 shows the high distribution of atoms, molecules in upper atmosphere presented as the international standard atmosphere (CIRA) in 1972, which was determined by the Space Research Committee (COSPAR).

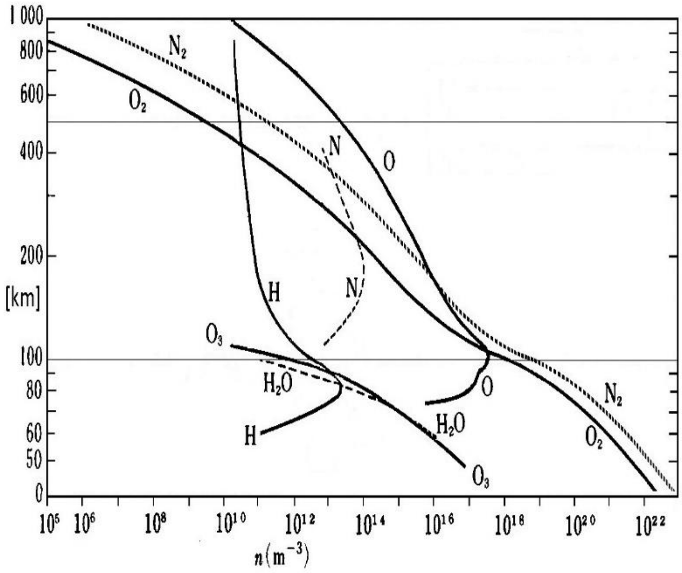

Fig.3. Altitude dependency of density on oxygen atom, oxygen molecule, ozone, nitrogen atom and nitrogen molecules, etc. (The figure was reproduced from [2])

There are no hydrogen molecules in the uppermost layer due to the weak gravity of Earth. But, the peak of the concentration of hydrogen atom in the Earth's atmosphere is between 100 km and 70 km. Those hydrogen atoms were produced from invaded protons by bond with electrons.

The energy state of atom is higher than that of molecule. Over 150km above the Earth, the oxygen atom (O) exists as the state of isolated atom. When the altitude becomes below 100km, the oxygen atom becomes the state of the molecule (O_2). Oxygen atoms and oxygen molecules are bonded as the state of ozone (O_3) at the lower temperatures.

The altitude that ozone concentration peaks is 25km. The ozone layer contributes to the temperature rise by absorbing the ultraviolet rays of sunlight. Moreover, the temperature rises according to lowering the altitude via the pressure becomes increases in the troposphere.

The distribution of ozone (O_3) is measured by Earth probe and Aurora satellites. The concentration of ozone is high at high latitudes in the northern hemisphere, and ozone concentrations are low in the vicinity of the equator and the Antarctic region. Seasonal changes in the amount of ozone are near the North Pole in early spring, and in Antarctica, ozone holes are created in early spring [13].

It is also possible that the temperature above Antarctica will be very low, ice crystals will increase, and ozone will disappear. The details of the characteristics of ozone have not yet been well understood.

4. 2. Temperature on the upper atmosphere

The altitude dependence of the temperature of the Earth's atmosphere changes complexly as shown in Fig.2. On Earth, there is a troposphere in upper atmosphere of about 12 km or less, and in the troposphere, higher altitudes reduce temperatures by -6.5 °C/km on average.

But at the altitude becomes higher than 12 km in the stratosphere, the temperature of the atmosphere increases as shown in Fig.2. The peak of temperature is about 0°C in the vicinity of 55km. When the altitude is raised furthermore, the temperature decreases. The bottom of low temperature about -80° at altitude of around 85km.

The altitude dependence on complex atmospheric temperatures like Earth does not have Venus. It is believed that the atmosphere of early Earth and Venus were composed of H_2O and CO_2. The primitive sea was born on the surface of the early Earth of which temperature the water existed as a liquid. CO_2 dissolved into the water of the sea, and the CO_2 turned to limestones and moved to the rock sphere. But, the temperature of surface on the Venus has been high and cannot hold water in a liquid state. The upper layer of Venus's atmosphere has been H_2O and the lower layer has been CO_2. Venus does not have geomagnetism. So, the protons of the solar wind collide with the thick atmosphere of the Venus. There is a super rotation of the Venus that orbiting around the Venus at high speed. The driving force of the superrotation can be explained by the solar wind [10].

5. Effects of solar wind on the Earth's weather

5. 1. Upper winds in the stratosphere

As the stream of atmosphere around the earth, there is a west wind near the mid-latitude, and a trade wind near the equator [10].

By the way, the earth's rotation causes the equatorial surface speed to rotate in the counter lock-wise direction at 463m/sec. The solar wind that blows the east side accelerates the atmosphere in the direction of Earth’s rotation. But the solar wind that blows through the west side of the Earth slows down the flow of the atmosphere on the Earth. Since the earth's rotation axis is tilted, the influence of the solar wind which blows through the east side of the earth becomes strong in winter. Therefore, the solar wind is driven strongly by the west wind in winter.

There is a sudden temperature rise of several tens of degrees Celsius per week in the high latitude stratosphere of the northern hemisphere at the seasonal boundaries from winter to spring. The temperature rise begins in the upper stratosphere and is transmitted to the lower stratosphere. The phenomenon must be related with the solar wind.

Since the Sun rotates in a 25.4-day cycle, there is 2km/sec of anti-clock wise rotational speed near the equator of the Sun. There is the rotational component of the anti-clock direction of the solar wind. The solar wind hits the earth's midday-hemisphere, the molecules in the atmosphere rotate in the clockwise direction by the mechanism of gears. The trade wind in the region near the equator flows from east to west is derived by the rotational component of solar wind.

There are the North Pacific Ocean current and the Gulf of Mexico current those currents are divided by the Asian continent and the North American continent. But these currents are driven by the trade wind and west wind in the northern hemisphere. In the southern hemisphere, where there is the current surrounding Antarctica. The currents are driven by the trade wind and west wind in the southern hemisphere

6. Conclusion

This article described the characteristics of ionosphere by using a model in which high speed protons emitted from the Sun, and collide with atoms and molecules in the earth's upper atmosphere. The propagation of various radio waves in the ionosphere shows the relationship between the earth's upper atmosphere and the protons of the solar wind.

While the coupling between parallelly moving protons and free electron is repulsive, the magnetic coupling on the parallelly moving proton and proton is pull each other. The high-speed protons in the solar wind circulates along the magnetic field lines of the earth's geomagnetic field and enter the magnetosphere. The protons of the solar wind that is exercising at high speed are involved in the formation of the ionosphere. The model is useful in constructing the theory about the formation of the ionosphere.

Future issues include systematically collecting data to elucidate the behavior of charged particles in this wide area. In addition, The author reported the scenario that the chemical reaction between protons and primitive CO_2 produced liquid hydrocarbons those float on the water surface, and the organism was born in such environments [14]. The effects of the solar wind on the Earth are expected to develop in the field of the origin of life.

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