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A Physical Explanation for the Formation of Auroras

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Abstract

What mechanism causes the symmetrical distribution of two oval-ring auroras approximately around the geomagnetic poles but uneven brightness distribution of them? To answer this question, we firstly describe the charged particles like electrons or protons emitted from the Sun and the magnetic ions formed in the Earth's atmosphere. Then, the interaction dynamics of two-type particles between electron and ion is given under the non-relativistic limit. Finally, under the relativistic frame, auroras deduced are higher energy density formed by the orthogonal interaction of solar charged particles and geomagnetic ions in the narrow regions centered on the upper geomagnetic poles. The physical nature of ideal oval-ring auroras with uneven brightness distribution is an optical phenomenon that occurs when solar charged particles collide orthogonally with ions and the magnetic axis inclines to the solar radiation. For actual aurora distribution, the impact of multiple factors is discussed. Therefore, the aurora is a natural illustration of an orthogonal collider in the Earth's upper atmosphere.

Keywords

Aurora, Electron, Ion, Orthogonal Collision, Space Weather

1. Introduction

One of the most spectacular shows that the natural light offers in the northern latitudes is the so-called Aurora Borealis [1]. Aurora is a colorful plasma phenomenon that occurs due to the flow of charged particles (solar wind) from the Sun entering the Earth's magnetic field so that the brilliant and beautiful glow appears at clear-sky night near the north and south poles of the Earth. They are respectively referred as the Aurora Borealis (northern lights) near the north pole and Aurora Australis (southern lights) near the south pole. As early as the 13th century to the middle of the 18th century, 1538 days of Aurora Borealis were recorded below 55 degrees at the northern mid-latitudes [2]. At the Space-Weather website of USA [3], the northern lights are thought to be the result of accelerated electrons or strong electrically charged solar wind particles colliding with air molecules (or oxygen and nitrogen atoms) in the Earth's upper atmosphere. In these collisions, the electrons transfer their energy to the upper atmosphere thus exciting the atoms and molecules to higher energy states, so that beautiful color lights can be observed by human naked eyes in the high latitudes. The auroras typically form about 80 to 500 km above the Earth's surface and usually occur between 60 and 75 degrees of the latitude. Therefore, the first question is why do auroras occur frequently only in these ranges of latitude and altitude?

In the above process of forming the northern and southern lights, a key physical event is the acceleration of electrons and collision with other particles. It is generally believed that the acceleration of electrons is associated with the cause of geomagnetic storms during strong solar activities [4]. The Earth's magnetic fields converge and guide the electrons or other charged particles at the upper atmosphere such that auroras form two bright ovals approximately centered at the geomagnetic poles [5] [6]. The geomagnetic intensity is varied in the northern and southern hemispheres during geomagnetic quiet and disturbed times [7]. The geomagnetic activity reaches the maximum around the magnetic latitude of 70 degrees [8]. Auroral oval boundary dynamics is associated with geomagnetic storm intensity [9]. When stronger geomagnetic storms occur, auroras extend frequently equator-ward and increase the appearance of space weather activity [10] [11]. Therefore, auroras are considered as one of space weather phenomena. The best time to observe the aurora is at the mid-night in a cold winter because the skies must be clear, dark and free of clouds [12] [13]. Two questions can be asked here. Why the best time to observe the aurora is in clear skies and cold winter midnight? And how do high-energy electrons or other charged particles collide only with upper atmospheric molecules (or atoms) to excite new high-energy states during a solar activity?

Historically, auroras can only be observed by human naked eyes at the ground. Recent decades, satellites play an important role in the observation of auroras and the distribution of their ion-electron energies [14]. The Aurora Borealis and Aurora Australis have been observed by special all-sky sensor ultraviolet scanning imagers on board satellites. The global positioning system (GPS) phase scintillation caused by high-latitude ionospheric irregularities during an intense high-speed stream of the solar wind from April 29 to May 5, 2011, was observed using arrays of the GPS ionospheric scintillation and total electron content monitors in the Arctic and Antarctica [15]. Sequences of scintillation events were observed as the aurora brightened and/or drifted across the field of view of the all-sky imager. In the northern and southern hemispheres, the image captured an auroral arc brightening at the pole-ward edge of the auroral oval, with an arc being detached. Two successive auroral image scans showed that the oval-ring brightness was not uniform. Three oval-ring events of current aurora were also observed by satellite and ground imagers in the two hemispheres on May 16, 2005, August 26, 2018 and September 5, 2005 respectively [16]. The oval-ring current auroras appeared as auroral spots or arcs in the day, dusk or night side. Similarly, ring-oval auroras were also observed by the Galilean satellites at the Jupiter and its moons [17] [18]. The last question can be raised from the auroral image scans: what causes the pattern of oval-ring auroral arc with its distribution of inhomogeneous brightness?

It can be summarized that the formation of auroras is caused by high-energy electrons from the Sun entering the Earth's upper atmosphere in the narrow regions centered on the magnetic poles. The energy of molecules (atoms) in the upper atmosphere is limited so we need to examine whether the abnormal energy of the Sun's activity can collide with molecules (atoms) to form a new high-energy state. As a high-altitude space weather phenomenon, the first two questions are about the spatial and temporal distributions of auroras in the climate view, while the latter two questions are associated with the physical nature of auroral formation. These four questions need to be answered by a unified physical theory. Thus, this paper first describes how charged particles produced by the Sun and the Earth emit to space and then gives a microscopic description about how high-energy particles emitted from the Sun interact with the electronically charged Earth's particles in the narrow regions centered on the upper geomagnetic poles. The goal is to theoretically describe that the northern and southern lights are physically originated from the interaction of different charged particles. Finally, the paper gives conclusions and discussion.

2. Particles Produced by the Sun and the Earth

As space weather phenomena, the formation of auroras is inseparable from the space environment of the universe. In addition to the presence of various celestial bodies, including stars, planets and moons, the universe is also filled with radiation and reflection of particles from these celestial bodies. The Sun that can shine is the only star in the solar system. The Earth is a planet in the solar system with a geomagnetic field. The Moon is a natural satellite of the Earth without a magnetic field. We first discuss why three objects the Sun, Earth and Moon can emit or reflect radiation. The Moon is already a solid ball so that different layers can no longer be circled inside. The bright Moon can be seen by human naked eyes from the Earth at night because the Moon reflects the sunlight. Similarly, the Apollo astronauts on the Moon can also see our own beautiful Earth reflecting the sunlight. Stars outside our solar system also emit light beams and particles from far away, but their luminous and particle fluxes are too small, and their reflections on the Earth and Moon are also small.

As a planet in the solar system, the Earth is composed of multiple concentric layers of matter in different states. In the simplest form, the Earth is composed like an egg, with a core as its central part, a middle yolk as fluid layer, and a thin shell covered in the whole outside. The Earth's core is made up of heavy metals (iron-nickel core). The Earth's fluid layer is composed of mantle magma, and the Earth's crust is the continental-oceanic shell which is composed of lighter silicon-magnesium material and water. The outer part of the Earth's crust is an atmosphere up to 1000 km thick. Since large amounts of water vapor are concentrated in the layer more than 10 kilometers called the troposphere above the surface, daily weathers such as normal clouds and extreme storms occur in the troposphere. Auroras occur in the ionosphere that is about 80 kilometers above the surface, where temperatures of thermosphere are higher and there are fewer water vapor molecules and dust particles. Auroras formed over the Earth's poles are associated with the interaction between energetic ions in the upper atmosphere and the charged particles coming to there.

We now analyze possible magnetic fields of the above three celestial objects from the Earth to the Moon and the Sun. The compass used by ancient people for navigation has proved that the Earth is a huge magnet with a geomagnetic field. Electricity and magnetism are closely linked. There is a relative motion between the mantle magma layer and the solid core inside the Earth. The relative motion between the adjacent layers acts as electrical generators to produce the Earth's electric field and magnetic field. The Earth rotates around its axis. The geomagnetic field direction or polarity is reversed depending on whether the mantle rotates relative to the core fast or slow, which is called the geomagnetic field reversal. In the geological history of the Earth, the geomagnetic field has been inverted many times [19]. Geomagnetic inversion was recorded in sediments distributed parallel on both sides of the mid-ocean ridge [20] [21].

The remanent magnetization of lunar soils suggests that the formation and evolution of the Moon are similar to those of the Earth [22]. In the early days of the formation of the Moon, the relative motion between the lunar iron core and the lunar mantle magma layer also formed a magnetic field, which recorded on rocks and soils of the lunar crust. But the Moon is smaller in both size and mass than Earth, so it also evolves geologically faster than the Earth. Today's lunar core, mantle and crust have all solidified together so that there is no atmosphere and magnetic field surrounding the current Moon. The remanence on the Moon now is the lunar historical record of the relative motion of the lunar inner layers over geological time [23].

There is also relative motion between multiple layers in the interior of the Sun. Therefore, the Sun is a huge electrical generator, and there is also a huge solar magnetic field [24]. The relative motion of the different layers of the Sun forms a convective circulation in the latitudinal zone inside each circle and a motion of many vortexes in the horizontal plane of the same circle. These convective and vortex motions are local generators which form a local solar magnetic field that manifests itself as solar activities, such as the appearance of sunspots [25] [26]

[27]. In effect, these convective and vortex motions form nuclear fusion on the Sun. Scientists and engineers have continued to study the Sun's fusion process in hopes of one day using nuclear fusion to generate electricity [28] [29].

These charged particles excited from the solar activities have a high velocity. The momentum of a solar particle is the ability to break free from the mass inertia that originally moved in the same way as the Sun as a whole [30]. From Newton's point of view, it is to break free from the Sun's huge gravitational field. To use a formula, a particle with a little mass m on the Sun wants to leave the Sun. Thus, its acceleration $\boldsymbol{a}_m$ must be equal to or greater than the gravitational acceleration $\boldsymbol{g}_\Theta$ of the Sun on it

$$\boldsymbol{a}_m \geq \boldsymbol{g}_\Theta . \tag{1}$$

If a particle can break free from the Sun, it is an electron or proton. Electrons are constantly breaking free from the Sun's corona and radiate into space, with one beam reaching the Earth and the other reaching the Moon. The flux and intensity of solar particles reaching the Earth and Moon varies with the solar activities.

The Earth's particles, especially those in the Earth's atmosphere, are also trying to break free from the same inherent inertia as the Earth [30]. In Newton's gravitational discourse, the particles on the Earth also want to leave the geo-gravitational field and become particles heading into space. But the low-velocity relative motion between the inner iron core and the mantle magma layer is not powerful enough to get these particles out of the geo-gravitational field. Otherwise, the Earth's atmosphere would have disappeared long ago. For this reason, the low-velocity relative motion between the Earth's inner layers formed the geomagnetic field.

The Earth's materials can be roughly divided into three types: solid, liquid and gaseous. The Earth's core and crust are solid layer structures. The Earth's mantle, especially in the early days of Earth's formation, is a liquid magma layer. The global ocean above the Earth's crust occupies liquid water, but separated by continents so that it is not entirely circle-structured. The Earth's outer layer is structured by the atmosphere. Although the low-velocity relative motion between the Earth's inner layers cannot produce the ability of particles to leave the Earth, the electromagnetic field formed by the relative motion between the circle layers will change the motion and distribution of particles (ions) in the Earth's upper atmosphere.

The geomagnetic poles do not coincide completely with the geographical poles. There is a geomagnetic declination. The physical nature of the geomagnetic poles is the distribution of the Earth's electromagnetic field formed by the overall low-velocity fluid of the inner mantle relative to the inner core. In addition to the overall movement of the mantle layer relative to the inner core, there is also a local movement relative to the inner core and outer crust in the mantle fluid, which also forms local geomagnetic disturbances. Moreover, the local movement of the mantle relative to the Earth's crust can lead to earthquakes and volcanic activities. Volcanic activities on the mid-ocean ridges record the past information about changes in local geomagnetic fields and geomagnetic field reversals [31].

In Figure 1, the range that the magnetic field lines can reach is mainly in the atmosphere within 1000 km. Within this layer, the relatively dense magnetic field lines are located at the narrow areas over the north and south poles, while sparse lines are found in the vast areas over the mid-low latitudes. The density of magnetic field lines can be seen as places in the atmosphere where charged particles (ions) are dense and moving fast. Dense magnetic field lines around the north and south magnetic poles form a narrow area like a funnel-shaped distribution. It is an area in where exists a relatively high density of ions in the mid-upper atmosphere.

From the above analysis, we have shown that the Sun as a star and the Earth as a planet excite different particles. The relative motion between the different layers in the Sun's interior excites solar particles and radiates them into the surrounding space. The relative motion between the different layers in the Earth's interior excites ions in the Earth's atmosphere and moves around the Earth with magnetic field lines. The relative motion between the inner layers of the Moon has stopped, so that there is no magnetic field on the Moon now.

3. Interaction Dynamics of Two-Type Particles

According to the current understanding, auroras are the result from the solar charged particles interacting with the geomagnetic ions in the Earth upper atmosphere. Therefore, auroras are optical phenomena exhibited by the interaction of high-energy particles. We now analyze the dynamics of high-energy particles to see how this phenomenon is excited. Any particle in the universe has

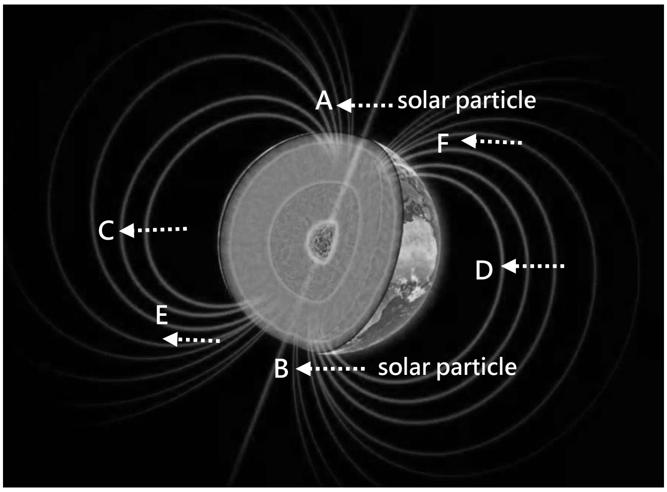

Figure 1. An ideal schematic pattern of the distribution of solar particles (dotted-line arrows) and geomagnetic field lines (white lines). Letters A, B, C, and D indicate four places where anomalous solar particles collide orthogonally with geomagnetic ions moved in the geomagnetic field lines. Letters E and F indicate two places where particles and ions respectively collide with their angles of 0 and 180 degrees along a straight line.

two forms of motion: curved motion and straight motion of acceleration or deceleration. A particle forms a curved motion as well as a motion of acceleration or deceleration, which is affected by the centripetal force and the mass force. We examine the interaction that occurs when two low-velocity particles α and β have a centripetal force $\frac{m}{r}v^2\boldsymbol{n}$ and mass force $ma\boldsymbol{k}$. The centripetal and mass forces of the two low-velocity particles are respectively

$$\boldsymbol{F}_\alpha = \frac{m_\alpha}{r_\alpha}v_\alpha^2\boldsymbol{n}_\alpha + m_\alpha a_\alpha \boldsymbol{k}_\alpha, \tag{2}$$

$$\boldsymbol{F}_\beta = \frac{m_\beta}{r_\beta}v_\beta^2\boldsymbol{n}_\beta + m_\beta a_\beta \boldsymbol{k}_\beta. \tag{3}$$

For the collision of two particles, their interaction can be expressed as the vector product of two forces, which is the shear stress [32]

$$\boldsymbol{\tau}_C = \left(\frac{m_\alpha}{r_\alpha}v_\alpha^2\boldsymbol{n}_\alpha + m_\alpha a_\alpha \boldsymbol{k}_\alpha\right)\times\left(\frac{m_\beta}{r_\beta}v_\beta^2\boldsymbol{n}_\beta + m_\beta a_\beta \boldsymbol{k}_\beta\right). \tag{4}$$

If the motion of acceleration or deceleration of particles is not taken into account, *i.e.*, $a_\alpha = a_\beta = 0$, we have

$$\boldsymbol{\tau}_C = \left(\frac{m_\alpha}{r_\alpha}v_\alpha^2\boldsymbol{n}_\alpha\right)\times\left(\frac{m_\beta}{r_\beta}v_\beta^2\boldsymbol{n}_\beta\right). \tag{5}$$

We use Equation (5) in **Figure 1** for the collision of a particle from the Sun with a particle in the Earth's upper atmosphere. It is well known that the vector-product of the two forces is another vector, namely $\boldsymbol{n}_\alpha \times \boldsymbol{n}_\beta = \boldsymbol{n}_\gamma$ so that the shear stress is usually defined as a force per surface area. This vector $\boldsymbol{n}_\gamma$ is perpendicular to the plane formed by those two vectors between $\boldsymbol{n}_\alpha$ and $\boldsymbol{n}_\beta$. The modulus of vector-product of the two forces based on Equation (5) is

$$\tau_C = \left(\frac{m_\alpha}{r_\alpha}v_\alpha^2\right)\cdot\left(\frac{m_\beta}{r_\beta}v_\beta^2\right)\sin\theta. \tag{6}$$

where r_α and r_β are the radius of two moving particles with their masses m_α and m_β as well as their velocities v_α and v_β, respectively. The letter θ is the angle at which two particles collide. The modulus reaches the maximum

$$\tau_C = 4\left(\frac{1}{2}m_\alpha v_\alpha^2\right)\left(\frac{1}{2}m_\beta v_\beta^2\right)\Big/\left(r_\alpha r_\beta\right) = 4E_\alpha E_\beta\Big/\left(r_\alpha r_\beta\right) \tag{7}$$

only when the collision angle between the two particles is orthogonal (90 degrees). Otherwise, when the collision angle between them is larger or less than 90 degrees, the modulus of shear stress will be reduced. Since the Sun rotates, it also rotates with the Milky Way. The Earth rotates and revolves around the Sun. Therefore, particles emitted by a star and the ions in a planet's atmosphere do not move in a straight line, but there is a centripetal motion with a radius.

Although the shear stress is another vector, we only concern its modulus which is really associated with whether it can produce light phenomena (new physical state) or not. In Equation (7), $E_\alpha = \frac{1}{2} m_\alpha v_\alpha^2$ and $E_\beta = \frac{1}{2} m_\beta v_\beta^2$ are energies of two particles. Before the collision, the two energies are separated. At the moment of the orthogonal collision, the energy of particle β has increased by $4E_\alpha$ times. The term $4E_\alpha E_\beta$ is a total energy at the collision moment. This total energy is originally scattered over a rectangular area by two radius r_α and r_β. Therefore, the term $4E_\alpha E_\beta / (r_\alpha r_\beta)$ can be simply referred to as energy density. Actually, after the orthogonal collision, two particles have been completely crushed into a new physical state, exhibiting a huge energy density. Before the collision of two particles, the total energy $4E_\alpha E_\beta$ on the area ($r_\alpha \times r_\beta$) is known and should be conserved with time. The total energy $4E_\alpha E_\beta$ will be concentrated on a very small three-dimensional space point A after the collision in Figure 1. The energy density of the orthogonal collision of two particles is extremely large and can be called as a new high-energy state or a plasma phenomenon.

The actual interaction between particles and ions differs from the above theoretical derivation in two differences. The first is the number difference between particle pairs. An actual aurora is produced by a large number of continuous solar particles interacting with geomagnetic ions. When a large number of solar particles collide orthogonally with a large number of geomagnetic ions, the energy density excited is huge, forming a new substance, which represents an aurora. In the above theory, we only give the interaction of a pair between a solar particle and a geomagnetic ion as an illustration. But the latter has theoretically given a clear explanation for the dynamics of the former's aurora formation.

The second is the difference in the velocity of particles. The particles used in the theoretical derivation process belong to the low-velocity state and use the non-relativistic limit. In fact, the velocity of particles emitted by the Sun to the Earth's poles is very high. The velocity of ions in the Earth's atmosphere along the geomagnetic field lines is also high. Thus, the relativistic momentum must be considered in the formation of auroras.

The relativistic momentum for a particle mass m_i and velocity v_i is

$$p_i = \gamma_i m_i v_i, \tag{8}$$

and the relativistic energy is

$$E_i = \gamma_i \left(m_i v_i^2 \right), \tag{9}$$

while

$$\gamma_i = \frac{1}{\sqrt{1 - v_i^2 / c^2}}. \tag{10}$$

is the Lorentz factor related to the speed of light c [33].

Thus, the high energy density $Q_{S,G}$ collided orthogonally by a solar particle and a geomagnetic ion is concentrated at the point A or B in a three-dimensional space. From Equation (7),

$$Q_{S,G} = \gamma_S \left(m_S v_S^2 \right) \gamma_G \left(m_G v_G^2 \right) = 4\gamma_S E_S \gamma_G E_G \tag{11}$$

where m_S and m_G are respectively masses of solar particle and geomagnetic ion with their velocity v_S and velocity v_G. Equation (11) indicates that the high energy density is the multiplication of energies between two-type particles. The space (or area by a particle thickness) after orthogonal collision of two particles is very small so that the energy density is very high. There are many points of orthogonal collisions between two-type particles over the polar atmosphere. These points form bright areas where they show Auroras. Here, only relativistic energy of particle interaction is considered. The wave-particle interaction will be discussed late.

4. Orthogonal Interaction between Solar Particles and Geomagnetic Ions

The upper magnetosphere of the Earth's atmosphere has higher temperatures so that it is called as the thermosphere. However, due to the asymmetry of the thermal distribution, the high-level atmospheric circulation around the poles is often not symmetrical relative to the north and south poles. Also, produced major total particle content varies at different latitudes and longitudes during enhanced magnetospheric storm processes, which showed the strong longitudinal and hemispherical asymmetry [34]. Therefore, the movement of various charged particles and ions around the polar region will also be relatively polar asymmetrical on the planetary scale, and even local disturbances will vertically occur. For example, regional temperature inversion can vertically form varied ion content. But they should still have a fundamental large-scale feature from the distribution of geomagnetic ions.

The spatial distribution of the geomagnetic field is not isolated and is affected by the solar wind (solar radiated or charged particles). How do solar particles affect the structure of the geomagnetic field? We first give an ideal structure while the actual asymmetrical or modified structure will be discussed late. Solar particles arriving near the Earth can be watched as moving in a straight line at a certain fractional speed of light. In **Figure 1**, solar particles reach six different points (A, B, C to F) in the geomagnetic field. When the solar particles ideally reach point A near the Earth's North Pole, they collide orthogonally with ions in the geomagnetic field. If the Sun is in an active phase, or the geomagnetic field is in an enhanced period, or both solar and geomagnetic activities are at an enhanced moment, an orthogonal collision at point A produces a higher energy state. The high-energy state there can present strong lights or colorful plasma phenomenon, which are the northern lights (Aurora Borealis). When other solar particles ideally reach point B near the South Pole, ions in the Earth's upper atmosphere collided orthogonally with solar particles, produce a new high-energy state symmetrical to point A and the excited the southern lights (Aurora Australis).

The interaction of solar particles reaching points E and F with geomagnetic ions in the Earth's upper atmosphere is not orthogonal, but two positions are symmetrical. We look at the linear collision between two particles happened in Figure 1. The linear collision is commonly used in all current colliders [33]. The rear-end collision and head-on collision of the two-type particles are set at the points E and F, respectively. The total energies of linear collision between a solar particle and a geomagnetic ion are addition or subtraction of their energies. The energy of rear-end collision at the point E is the subtraction.

$$E_E = \gamma_S E_S - \gamma_G E_G . \quad (12)$$

This is at the point E where the solar particle's speed is faster than that of the geomagnetic ion at the same direction when they collide.

The total energy of head-on collision at the point F is the sum or addition of their energies [33].

$$E_F = \gamma_S E_S + \gamma_G E_G . \quad (13)$$

It indicates that the solar particle is collided with the geomagnetic ion at the point F at the opposite direction.

The head-on collision and the rear-end collision only have total energy at the points E and F because their energy density is zero when the collision angle of two particles is 0 or 180 degrees based on Equation (6). Therefore, there should theoretically form two symmetrical oval rings of brightness over the two polar geomagnetic fields but the brightness along each oval ring is not symmetrically bright in one half than the other half. The oval light ring with a distribution of asymmetrical brightness is formed by because the Earth's axis is tilted relative to the solar radiation. The energy density of two-type particles collided at the points A and B reaches the maximum which formed new physical state while the energy density is zero at the points E and F without formed new physical state. This answers the question why the intensity distribution of an aurora is asymmetry, as observed by satellites. At the points C and D in Figure 1, the energy density of solar particles colliding orthogonally to the upper atmospheric ions along the geomagnetic field lines is low because the ion density is sparse there. Solar radiation can reach the point D on the front of the Earth, where solar particles collide with few ions orthogonally. Since this happens during the daytime, people on the Earth cannot see the abnormal energy formed by the collision. Actually, near magnetic local noon, the diffuse aurora was often observed in structured forms [35]. The point C located on the back of the Earth is in the nighttime sky, where no solar particles interact with geomagnetic ions.

A comprehensive investigation of the interaction in Figure 1 shows that solar particles interact with geomagnetic ions on the dense band of geomagnetic field lines at the poles to form a high-energy distribution or new physical state, which is where the aurora appears. As the Earth rotates, the strong aurora also changes with the position of the orthogonal collision between solar particles and geomagnetic ions. When their collision angle is less than or larger than 90 degrees, the aurora is weak according to Equation (6) for their modulus.

The density and velocity of polar-area ions vary with particle flow and the strength of geomagnetic field. When the strength and density of ions in the geomagnetic field are abnormal and, at the same time, the solar winds are abnormal, the energy density excited by the orthogonal collision between solar particles and geomagnetic ions will be intensified, forming abnormal auroras. Therefore, the spatial distribution of auroras in the two polar areas is neither completely symmetrical, nor periodic in time.

Whether auroras can be observed on the ground is affected by many weather conditions. In a rainy weather day, auroras are not visible there over the two polar areas. The abnormal distribution of ions and other particles in the ionosphere can also affect the formation of auroras, and even change the color of auroras through reflection and refraction. Therefore, clear skies and cold winter are possibly better conditions to see auroras in the two polar areas.

5. Conclusions

On the basis of collecting people's cognition of auroras, this paper uses a unique dynamic theory to reveal the physical nature of auroral formation. Auroras are optical phenomena in which atmospheric ions interact with solar charged particles at the height of the Earth's polar ionosphere. When the geomagnetic field is abnormal or/and an active solar phase, solar charged particles and geomagnetic ions will collide more violently in the polar space-time domain, forming a super strong auroral phenomenon. The theoretical distribution of high energy density or new physical state formed by the orthogonal collision of two-type particles can be applied to explain auroras occurring at the two poles of the Earth.

Theoretically, the maximum energy density can only occur at the points A and B from **Figure 1**, but high-energy rays produced by the new physical state, known as auroras, can only be observed over the polar areas at clear night. There is no auroral light at the points E and F because only the rear-end collision and the head-on collision appear there respectively. Outside the points E and F, auroras are not as strong as at the points A and B. The reason is that the collision angle between the solar particles and the Earth's atmospheric ions is larger or less than 90 degrees.

The theory in this paper and **Figure 1** are sufficient to answer the four questions raised. The fact that auroras often appeared at 60 - 75 degree latitudes and 80 - 500 km altitudes is determined by the condition of orthogonal interaction between the solar charged particles and geomagnetic ions. The auroras are the optical phenomena or the high-energy or new physical state of two types of high-speed particles interacting in the upper atmosphere. The oval-ring aurora observed by satellites shows that one part is brighter than the other with a reason because the Earth's axis is tilted relative to the solar radiation. Clear skies and cold winter midnight are the best chances to observe auroras because the tropospheric weather environment sometimes influences the observer's perspective, not a physical one.

In each of planetary atmosphere of the solar system, and even in the atmosphere of natural moons, auroras at their two poles can often appear as long as they have their own magnetic fields. Another common condition for forming auroras is the solar activity. The Jupiter and its moons also have distributed auroras at their two polar areas. All auroras on the two polar ionospheres of planets and moons show an oval-ring distribution of brightness because their axes are tilted to the solar radiation.

The physics community has spent a lot of efforts building accelerators and colliders [36] [37] [38]. Their aim is to increase the speed and energy of known particles through accelerators. Current colliders are used to producing higher energies and tried to form new matter through a head-on collision. Since head-on collisions are linear ones, the formed energy is limited and predictable [39]. Therefore, in current linear colliders, it seems difficult to achieve the further goal that physicists are looking for new substances or new physical state. The auroras that occur in the middle and upper parts of the polar geo-ionospheres are a natural orthogonal collider. This paper has explored the formation mechanism of auroras, which implies that the dream of the scientific community to find new matter can be enhanced if orthogonal high-energy colliders can be built.

6. Discussion

This paper presents a symmetrical or idealized model of the geomagnetic field that expresses the interaction of charged particles from the Sun with geomagnetic ions to form oval-ring auroras with uneven brightness distribution near the poles. Auroras are anomalous space weather that occurs in the ionosphere of the upper atmosphere, like extreme weather in the troposphere, so that they have their corresponding anomalous patterns, but each weather event has differences in intensity, coverage, and duration. For the possible causes of aurora formation in multiple structures and multi-luminous distributions, we give the following discussion.

1) Asymmetric geomagnetic distribution under the interaction of the Sun's magnetic field with the Earth's magnetic field. As previously described in the solar system, the Earth's magnetic field is not the only one that exists. The Sun has a magnetic field by the strength which affects the flow of high-energy charged plasma particles in all directions to form the solar wind. When the solar wind reaches the vicinity of the Earth, it interferes with the magnetic field generated by the Earth, flattening it on the sunny side of the Earth facing the Sun and stretching it into a near-Earth magnetotail on the side facing away from the Sun [40]. As magnetic field lines pass through a distorted magnetic field, they break and reconnect. When the solar wind magnetic field and the Earth's magnetic field are tilted, the Earth's magnetic field will produce a deviation from the relative symmetry distribution between the north and south poles, which will also lead to a deviation of the north and south lights related to the symmetrical distribution. As a result, there are differences in the Earth's magnetic field between ionospheric conjugate points, as well as differences in solar particle exposure

between the two magnetic hemispheres. These differences lead to asymmetries in ionospheric convection, thermosphere wind, currents, magnetic field disturbances, ion outflow, electron density, and aurora emission [41]. To be precise, these asymmetries are deviations from their relative symmetrical distribution as shown in **Figure 1** by the ideal pattern.

2) Charged particles in the atmospheric inversion layer cause auroral noise. The inversion layer in the atmosphere is a perturbing environment that can cause many kinds of extreme weather, which concentrates pollutant materials and produces photochemical effects. The near-surface inversion layer in the troposphere is the environmental conditions that form polluted haze weather and ozone weather [42] [43]. In the thermosphere, atmospheric inversions are also formed on cold nights, resulting in changes of ion concentrations and abnormal ion movements there. As a result, when particles from the Sun hit the abnormally distributed and moving ions in the inversion layer, the charged particles collide and discharge at different angles, resulting in aurora noise. The inversion layer can have a significant impact on the optical phenomenon linked to the mechanism that modifies the symmetrical distribution of two auroras in an oval ring since the solar-charged particles could no longer entirely collide by a perpendicular angle with the ions. Thus, such inversion noise can cause the two oval ring auroras to deviate from the symmetrical distribution.

3) Effect of wave-particle interaction on the precipitation of energy particles. In the upper atmosphere, strong magnetosphere-ionosphere coupling plays an important role in wave-particle interactions [44]. Relativistic effects need to be considered during wave-particle interactions. Wave-particle interactions can cause relativistic electrons to simultaneously settle into isolated proton auroras. We believe that in wave-particle interactions, orthogonal collisions between them are still an important mechanism for electrons or protons to excite new energy. In the ionosphere, charged particles of the solar wind collide with oxygen and nitrogen atoms through wave-particle interactions. This release of collision energy allows people to observe colorful auroras. We speculate that only orthogonal collisions of solar wind particles with atmospheric particles are likely to yield higher anomalous energies and accelerate the velocity of electron groups during the last leg of the journey. The interaction of electrons and the Alfvén waves also plays a definitive role in the production of Earth's auroras [45] [46]. To generate energies of tens of keV and of relativistic electrons, only orthogonal interactions between electrons and Alvin waves are likely to have greater electron acceleration and auroras.

4) Possible formation causes of diffuse and discrete auroras. Auroras can be divided into diffuse and discrete (or pulsating) auroras [47]. They should be manifestation on the two magnetic conjugate regions involving complex interactions between ionospheric particles and energies. The difference between diffuse auroras and discrete auroras is the intensity of light, and its physical nature may be the difference in energy density as described from **Figure 1**. On the equator-

ward side of the dayside cusp there often appear diffuse auroras [48]. Thus, the diffuse aurora defines the extent of the auroral zone while the discrete auroras are sharply defined brightness features within the diffuse aurora. The intensity of solar activity and geomagnetic anomalies will not be exactly the same every time, so the collision angles and energy density of particle interactions or wave-particle interactions will be different. Therefore, the spatial and temporal distribution of auroras is associated with a complex space weather process, which has an intrinsic physical pattern and differences in the intensity, coverage and persistence of each process.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Laroussi, M. and Akman, M.A. (2014) *The IEEE Transactions on Plasma Science*, **42**, 2662-2663. https://doi.org/10.1109/TPS.2014.2326559

[2] Schlamminger, L. (1992) *The Journal of Atmospheric and Solar-Terrestrial Physics*, **54**, 989-993. https://doi.org/10.1016/0021-9169(92)90065-S

[3] Space Weather (2016) What Are Northern Lights? http://www.swpc.noaa.gov/phenomena/aurora

[4] Cardenas, F.M., Sanchez, S.C. and Dominguez, S.V. (2016) *Advances in Space Research*, **57**, 257-267. https://doi.org/10.1016/j.asr.2015.08.026

[5] Elphinstone, R.D., Murphree, J.S., Hearn, D.J., *et al.* (1995) *Journal of Geophysical Research*: *Space Physics*, **100**, 12075-12092. https://doi.org/10.1029/95JA00326

[6] Elphinstone, R.D., Hearn, D.J., Cogger, L.L., *et al.* (1995) *Journal of Geophysical Research*, **100**, 12093-12102. https://doi.org/10.1029/95JA00327

[7] Zhao, K., Jiang, Y., Men, K.P., *et al.* (2014) *Chinese Journal of Geophysics*, **57**, 3715-3728.

[8] Viljanen, A. and Tanskanen, E. (2013) *Earth Planets and Space*, **65**, 45-49. https://doi.org/10.5047/eps.2012.05.014

[9] Edemskiy, I.K. and Yasyukevich, Y.V. (2022) *Remote Sensing*, **14**, 5486. https://doi.org/10.3390/rs14215486

[10] Hapgood, M.A. (2011) *Advances in Space Research*, **47**, 2059-2072. https://doi.org/10.1016/j.asr.2010.02.007

[11] Tsurutani, B.T., Lakhina, G.S. and Hajra, R. (2020) *Nonlinear Processes in Geophysics*, **27**, 75-119. https://doi.org/10.5194/npg-27-75-2020

[12] Pihlaja, P.M. (2012) *Acta Borealia*, **29**, 119-136. https://doi.org/10.1080/08003831.2012.732281

[13] Johannesson, G.T. and Lund, K.A. (2017) *Annals of Tourism Research*, **63**, 183-190. https://doi.org/10.1016/j.annals.2017.02.001

[14] Sauvaud, J.A., Barthe, H., Aoustin, C., Thocaven, J.J., Rouzaud, J., Penou, E., Popescu, D., Kovrazhkin, R.A. and Afanasiev, K.G. (1998) *Annales Geophysicae*, **16**, 1056-1069. https://doi.org/10.1007/s00585-998-1056-z

[15] Prikryl, P., et al. (2013) *Annales Geophysicae*, **56**, R0216. https://www.annalsofgeophysics.eu/index.php/annals/article/view/6227

[16] Zhang, Y.L. and Paxton, L.J. (2019) *The Journal of Atmospheric and Solar-Terrestrial Physics*, **184**, 1-4. https://doi.org/10.1016/j.jastp.2019.01.005

[17] Mura, A., Adriani, A., Connerney, J.E.P., *et al.* (2018) *Science*, **361**, 774. https://doi.org/10.1126/science.aat1450

[18] Belenkaya, E.S. (2020) *Solar System Research*, **54**, 85-95. https://doi.org/10.1134/S003809462002001X

[19] Malinverno, A., Quigley, K.W., Staro, A. and Dyment, J. (2020) *Journal of Geophysical Research*: *Solid Earth*, **125**, e2020JB020034. https://doi.org/10.1029/2020JB020034

[20] Rea, D.K. and Blakely, R.J. (1975) *Nature*, **255**, 126-128. https://doi.org/10.1038/255126a0

[21] Fujiwara, T. and Fujimota, H. (1998) *Journal of Geophysical Research*: *Solid Earth*, **103**, 30335-30349. https://doi.org/10.1029/1998JB900015

[22] Fuller, M. (1972) *Science*, **178**, 154-156. https://doi.org/10.1126/science.178.4057.154

[23] Runcorn, S.K. (1983) *Nature*, **304**, 589-596. https://doi.org/10.1038/304589a0

[24] Bumba, V. and Howard, R. (1965) *Science*, **149**, 1331-1337. https://doi.org/10.1126/science.149.3690.1331

[25] Lewis, E.P. (1908) *Nature*, **78**, 569-570. https://doi.org/10.1038/078569d0

[26] Cram, L.E. (1979) *Nature*, **282**, 133-134. https://doi.org/10.1038/282133a0

[27] Livingston, W.C. (1982) *Nature*, **297**, 208-209. https://doi.org/10.1038/297208a0

[28] Petrescu, F. and Petrescu, R. (2020) *Independent J. Management & Production*, **11**, 1835-1855. https://doi.org/10.14807/ijmp.v11i3.930

[29] Baramsai, B., Benyo, T., Forsley. L. and Steinetz, B. (2022) *IEEE Spectrum*, **59**, 32-37. https://doi.org/10.1109/MSPEC.2022.9729961

[30] Qian, W (2022) *Journal of High Energy Physics*, *Gravitation and Cosmology*, **8**, 184-194. https://www.scirp.org/journal/jhepgc https://doi.org/10.4236/jhepgc.2022.81014

[31] Valet, J.P., Fournier, A., Courtillot, V. and Herrero-Bervera, E. (2012) *Nature*, **490**, 89-93. https://doi.org/10.1038/nature11491

[32] Qian, W. (2022b) *Journal of High Energy Physics*, *Gravitation and Cosmology*, **8**, 417-431. https://doi.org/10.4236/jhepgc.2022.82032

[33] Workman, *et al.* (2022) *Progress of Theoretical and Experimental Physics*, **2022**, 083C01.

[34] Ngwira, C.M., Habarulema, J., Astafyeva, E., *et al.* (2019) *Journal of Geophysical Research*: *Space Physics*, **124**, 7123-7139. https://doi.org/10.1029/2018JA026172

[35] Han, D.S. (2021) *Frontiers in Astronomy and Space Sciences*, **8**, Article ID: 725677. https://doi.org/10.3389/fspas.2021.725677

[36] Litvinenko, A.G. (2007) *Particle and Nuclei*, **38**, 204-231. https://doi.org/10.1134/S1063779607020037

[37] Bruning, O., Burkhardt, H. and Myers, S. (2012) *Progress in Particle and Nuclear Phys.*, **67**, 705-735. https://doi.org/10.1016/j.ppnp.2012.03.001

[38] Normile, D. and Cho, A. (2019) *Science*, **363**, 911-912. https://doi.org/10.1126/science.363.6430.911

[39] Qian, W. (2022) *Journal of Modern Physics*, **13**, 1440-1451. https://doi.org/10.4236/jmp.2022.1311089

[40] Man, H.Y., Zhou, M., Deng, X.H., *et al.* (2018) *Geophysical Research Letters*, **45**, 8729-8737. https://doi.org/10.1029/2018GL079778

[41] Ambrosino, D., Amata, E., Marcucci, M.F., *et al.* (2009) *Annales Geophysicae*, **27**, 2423-2438. https://doi.org/10.5194/angeo-27-2423-2009

[42] Qian, W.H. and Huang, J. (2019) *Science of the Total Environment*, **647**, 878-887. https://doi.org/10.1016/j.scitotenv.2018.07.408

[43] Qian, W.H., Xu, M. and Ai, Y. (2022) *Air Quality*, *Atmosphere & Health*, **15**, 1699-1711. https://doi.org/10.1007/s11869-022-01208-w

[44] Ni, B.B. and Thorne, R.M. (2012) Recent Advances in Understanding the Diffuse Auroral Precipitation: The Role of Resonant Wave-Particle Interactions. In: Summers, D., Mann, I.R., Baker, D.N. and Schulz, M., Eds., *Dynamics of the Earth's Radiation Belts and Inner Magnetosphere*, American Geophysical Union, Washington DC, 291-302. https://doi.org/10.1029/2012GM001337

[45] Watt, C.E.J. and Rankin, R. (2010) *Journal of Geophysical Research*: *Space Physics*, **115**, A07224. https://doi.org/10.1029/2009JA015185

[46] Mottez, F. (2012) The Role Alfven Waves in the Generation of Earth Polar Auroras. *Workshop on Waves and Instabilities in Space and Astrophysical Plasmas*, Vol. 1439, 3-25.

[47] Nishimura, Y., Lessard, M.R., Katoh, Y., *et al.* (2020) *Space Science Reviews*, **216**, Article No. 4. https://doi.org/10.1007/s11214-019-0629-3

[48] Taguchi, S., Hosokawa, K. and Ogawa, Y. (2019) *Journal of Geophysical Research*: *Space Physics*, **124**, 10778-10793. https://doi.org/10.1029/2019JA026895