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Aurora: Mechanism and Excitation Process

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Abstract: This paper reviews our current understanding of Aurora. Aurora is a luminous glow observed near the polar regions. We have provided a brief account of the history of auroras. Basic features and types of aurora are discussed involving the spatial and temporal variations in auroras. Magnetic reconnection and loss cone are reviewed to understand the formation of auroras. Pitch angle diffusion and acceleration mechanisms involved in the formation of diffuse and discrete auroras are explained. Recent advances made in the auroral research and the impact of auroras on our daily life are briefly discussed. The data about the recent aurora formation over the poles is also provided.

Keywords: aurora formation • magnetic reconnection • pitch angle diffusion

Introduction

Aurora is an astronomical phenomenon when coloured lights seem to shimmer in the sky. Colourful blue, red, yellow, green and pink lights gently shift and changes shapes like softly blowing curtains. Auroras are visible almost every night near polar region. The auroras visible near northern polar region are known as "Aurora Borealis" and those appearing in southern polar region are called "Aurora Australis". Auroras are formed due to the emissions in the Earth's ionosphere. These emissions are caused by the energy transfer during collisions between the ions in the ionosphere and the energetic particles entering the ionosphere from the Earth's magnetosphere. As a result of this energy transfer the bounded electrons of the ions moves to excited energy states, and the photons released during their transition back to the ground states appears as aurora. The various methods by which the particles from magnetosphere enters the ionosphere produces different types of auroras such as diffuse auroras and discrete auroras (Akasofu 2007). Auroral shape exhibits temporal, longitudinal and latitudinal variations. Longitudinal variations involves changes with local time, discrete arcs are observed in pre-midnight auroras and post-midnight auroras shows irregular behaviour (Akasofu 1964).

Ground and satellite based studies has confirmed that the auroral arcs are observed most commonly in an oval shape region around the poles known as auroral oval see Fig. 1. It maps the field lines that goes through plasma sheet (Baumjohann and Treumann 1996). The oval is dynamic in nature, it's boundaries shows seasonal variations and is also affected by the changes in geomagnetic conditions (Jayachandran et al. 2008). The Auroral oval moves equatorward during storms. The magnetic data from ground based observatories can be used to calculate the amount with which the auroral boundary moves towards the equator (Blake et al. 2021). Small scale auroral forms (ranging from a km to 10s of km) such as curls, spirals and folds have also been observed and their generating mechanisms depends on plasma instabilities such as Kelvin Helmholtz instability (Wagner et al. 1983). The spatial scale of auroras ranges from global to less than 100 m and have temporal range of few milliseconds to few hours (Paschmann et al. 2003). A number of these variations are quasiperiodic in space and time such as pulsating and flickering auroras (Jones 1974).

Historical Background

The relation between auroras and magnetic field disturbance was discovered in 1741. With the invention of discharge tube in 1753, speculations about aurora being a discharge phenomenon started. Loomis in 1860 prepared the first map of auroral zone. Fritz extended Loomis's work and in 1874 he published his isochasms, along these lines the average frequency with which auroras are visible is equal. Through Fritz's work it was evident that auroral frequency varied in consonance with the waxing and waning of sunspots (Eather 1980). Harry Vestine (1944) use additional data to refine Fritz's isochasm map (Vestine 1944). By 1971 with the help of satellite observations, the idea of auroral zone was replaced by the more accurate auroral oval, see Fig. 1.

It was believed that auroras have a fixed pattern of activity with respect to the sun. (Fuller and Bramhall 1937; Heppner 1954). At any location on earth for a particular observer this behaviour was even true statistically. But simultaneous observation of the aurora from different location instead of a single observation point, did not agree with the long held idea of fix pattern auroral activity. It was also observed that the activity pattern often repeat itself 2-3 times during a single active night.

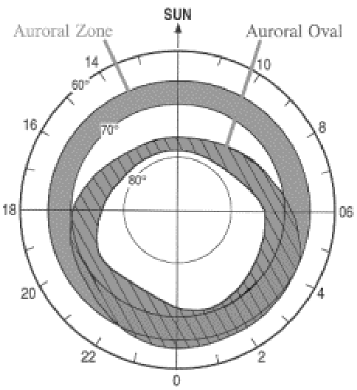

Fig. 1: The auroral zone and oval using magnetic local time and geomagnetic latitude as coordinate system (Akasofu 1967).

This transient phenomenon is known as auroral substorm (a term given by Sydney Chapman) see Fig. 2 (Akasofu 1964). The observations of various satellites eventually give the confirmation for the concept of auroral substorm (Craven et al. 1984). S.I. Akasofu and Sydney Chapman came to the conclusion that a large number of auroral substorms results in the formation of an auroral storm (Akasofu 1964).

Kristian Birkeland suggested that the beam of electrons given out by the sun is responsible for the auroras. On reaching Earth these rays were strongly affected by its magnetic field, which guide the electrons to the high latitude regions where they eventually form auroras (Akasofu 1979). In 1903, analysis of magnetic data led Birkeland to conclude that, during an aurora large current (known as Birkeland current) flowed along magnetic field lines (Birkeland 1913).

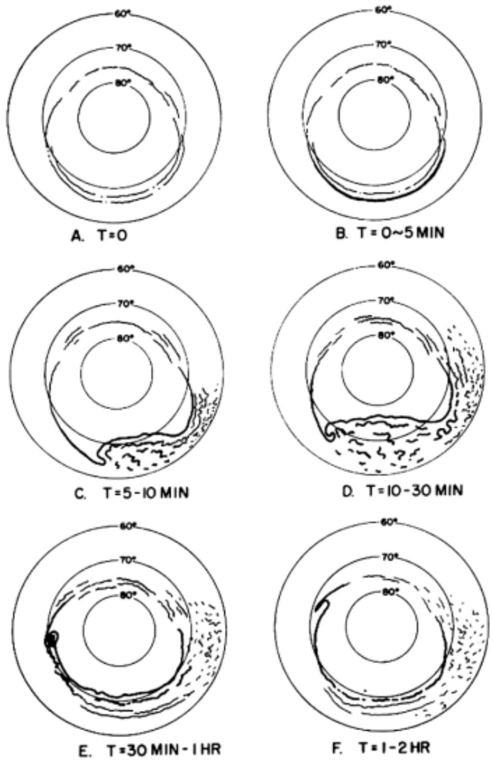

Fig. 2: The development of auroral substorm observed from above the geomagnetic pole (Akasofu 1964).

Later Chapman-Ferraro developed theory of magnetic storms which could be used to explain auroras (Chapman and Ferraro 1931). In order to explain magnetic storms and auroral formation, electric field theory was proposed by Alfven (Alfven 1939) . It assumes that the sun emits an electrically polarised beam of rarefied ionized gas. According to this theory the beam consists of a magnetic field. This magnetic field behave as it is frozen in a medium of high conductivity. An electric field is produced by this magnetic field due to the motion of the beam.

According to the leaky bucket theory, the radiation belts acts as the particle reservoir. Loss of particles from these reservoirs causes the visible aurora. Thus there were many theories proposed in order to give explanation regarding the mechanism of aurora, the most widely accepted one is of magnetic reconnection (Axford and Hines 1961).

Methodology

This study adopts a review-based approach grounded in extensive literature and data analysis to understand the formation and mechanisms of auroras. Key concepts such as magnetic reconnection, pitch angle diffusion, and particle acceleration have been explained using peer-reviewed scientific literature, observational satellite data, and historical auroral theories. Visual representations and figures are taken from previously published sources to explain complex phenomena like auroral substorms, magnetic mirror effects, and geomagnetic storms. Emphasis is placed on correlating classical mechanisms with recent advancements, including the integration of satellite missions (e.g., THEMIS, Van Allen Probes) and computational modeling approaches (e.g., machine learning-based auroral forecasts). The study synthesizes data from both ground-based and space-based observations to provide a comprehensive understanding of auroral excitation processes.

Results and Discussion

Mechanism for Aurora formation

Geomagnetic storms are caused by the interaction of interplanetary magnetic field (IMF) with Earth's magnetic field (Gonzalez et al. 1994). Due to these interactions magnetosphere and ionosphere experiences an increase in plasma movement and electric current. During substorms energy is released from magnetotail and is injected in inner magnetosphere and ionosphere. Reconnection in magnetotail initiates the substorm onset sequence. These substorms produces strong electric currents and aurora due to the release of energy from the magnetotail. Field aligned currents are responsible for controlling the plasma energy dissipation. Fast tailward expansion of magnetotail dipolarisation followed by the restretching of inner plasma as substorm undergoes expansion and during recovery phase results in rapid poleward then slow equator ward movement of the substorm aurora (Panov et al. 2016).

Adverse effects are produced by the storms occurring during high solar activity and they produce global scale aurora. This is because they accelerate electrons in radiation belts and also energizes ion in ring current (Angelopoulos et al. 2020). Thus, these disturbances of the geomagnetic field are responsible for auroral display.

Magnetic Reconnection

Magnetic reconnection can be roughly defined as plasma flow such that some magnetic field lines in it, passes a neutral point or line. If flow occurs at the neutral point and field's direction is not definite, then the electric field produced by the motion cause acceleration of particles leading to the fast jets of plasmas. These plasma jets flow away from the neutral line (Pontin and Priest 2022). The reconnection between geomagnetic field and IMF releases magnetic energy and particle acceleration could be produced. Dungey was first to use reconnection in magnetospheric physics (Dungey 1961). He suggested that a neutral point of type X present at the front of magnetosphere is responsible for reconnection between earth's magnetic field and IMF. This forms an open field line like structure whose one end is on earth and other end being far off in space.

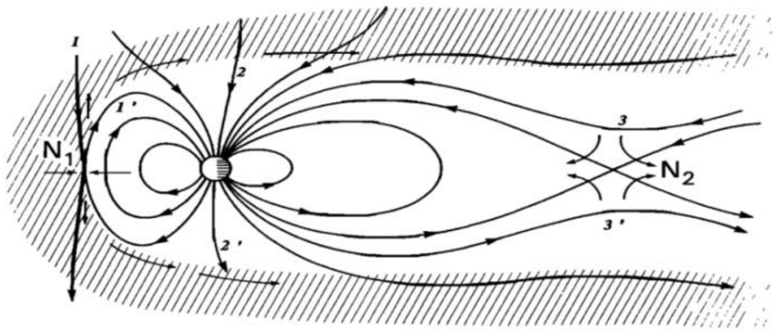

Fig. 3: Geomagnetic field and IMF depicting the process of magnetic reconnection (Stern 1996).

As shown in Fig. 3, merger of the lines 1 and 1' at the X type neutral point (denoted by N_1) forms the open lines 2 and 2'. These lines being embedded in the solar wind are then carried towards tail it, thereby acquiring the position 3 and 3'. In the tail eventually an IMF line is produced which is carried away by solar wind. At the same time a closed field line attached to the earth is also produced. This closed field line then flow towards sun until it becomes line 1' which undergoes reconnection with 1. Magnetic reconnection occurring at N_1 gives very little energy to plasma .It's main function is to produce open field lines , which are linked to ionosphere as well as to the solar wind. Such lines can act as dynamo circuit because flow of electric currents along these lines is much easier. This dynamo can cause electric current and fields in the polar ionosphere.

Magnetic mirror and loss cone

The magnetic field configuration which can trap plasma particles is known as magnetic mirror. The magnetic moment of the charge particle is one of the adiabatic invariant of motion (Baumjohann and Treumann 1996). Therefore in non-homogeneous magnetic field particle gets bounced back (or reflected) while moving into region of stronger fields (Chen 2016).

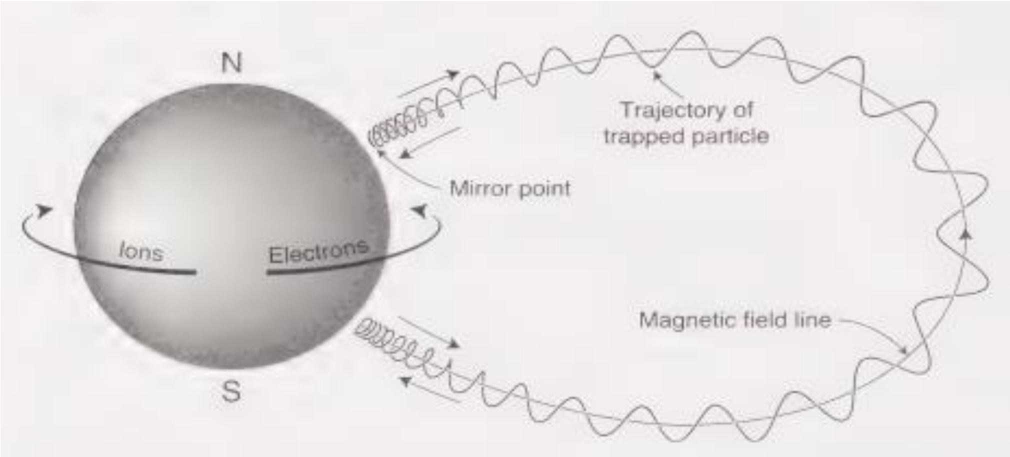

Fig. 4: Bounce motion and drift motion of charge particles in geomagnetic field (Baumjohann and Treumann 1996).

In non-homogenous field $\boldsymbol{B}$ a particle experiences both curvature drift $\boldsymbol{V_C}$ and gradient drift $\boldsymbol{V_G}$ in the same direction simultaneously, the combined drift $\boldsymbol{V_{GC}}$ is given by:

$$\boldsymbol{V_{GC}} = \boldsymbol{V_G} + \boldsymbol{V_C} = \frac{m}{q}\frac{\boldsymbol{R_c} \times \boldsymbol{B}}{R_c^2 B^2}\left(v_{\parallel}^2 + \frac{1}{2}v_{\perp}^2\right) \quad (1)$$

where m is mass, q is the charge on particle, $\boldsymbol{R_c}$ is the radius of curvature vector pointing from the center of curvature to the particle, $v_{\parallel}$ and $v_{\perp}$ are velocity components parallel and perpendicular to magnetic field respectively (Chen 2016).

As shown in Fig. 4 the charge particles move back and forth between the poles which acts as mirror points and undergoes drift longitudinally due to the combined drift. The drift motion also produces ring current in east to west direction. This leads to a tire shaped shell trajectory of the particle encircling the earth (Baumjohann and Treumann 1996).

But the trapping of particles is not perfect. For a coaxial magnetic mirror the ability to trap particles is given by mirror ratio B_m/B_0 where B_m is the strength of magnetic field (in strong field region) where reflection takes place and B_0 is the strength at the center (in the weak field region), hence $B_m > B_0$. Consider a particle moving in a coaxial magnetic field. Let at the center of the mirror system, pitch angle is α_0 and field strength is B_0. Now consider a location within magnetic field where field strength is B, pitch angle is α, mass of particle is m and the particle velocity is v then, from the invariance of magnetic moment μ,

$$\frac{1}{2}mv^2\frac{\sin^2\alpha}{B} = \frac{1}{2}mv^2\frac{\sin^2\alpha_0}{B_0} \quad (2)$$

$$\frac{\sin^2\alpha}{B} = \frac{\sin^2\alpha_0}{B_0} \quad (3)$$

At the reflection point $B = B_m$ and $\alpha = \pi/2$ i.e. where the particle is reflected back $sin^2\alpha_0/B_0 = 1/B_m$. This gives

$$sin^2\alpha_0 = \frac{B_0}{B_m} = \frac{1}{R_m} \quad (4)$$

where $B_m/B_0 = R_m$ the mirror ratio. The above equation gives the minimum value of the pitch angle required in the weak field region so that the particle can experience reflection. For given value of mirror ratio if the pitch angle is greater than α_0, then the particle is reflected but if the pitch angle is less than α_0, then the particle cannot be reflected and trapping is not perfect (Chen 2016).

The equation (4) defines a cone shaped region in the velocity space known as loss cone. Particles having their velocity within the loss cone are not confined, and are lost into the nearby space. These particles enter the ionosphere in the upper atmosphere, resulting in aurora.

Pitch angle diffusion and acceleration mechanisms

Electrons can enter ionosphere from magnetosphere mainly by two processes, pitch angle diffusion, and acceleration along magnetic field lines. Diffuse auroras are produced by pitch angle diffusion and the discrete auroras are generated by the acceleration along field lines.

Electron pitch angle diffusion is the predominant method for producing large scale auroras. This diffusion process also provides the auroral oval its unique shape (Liou et al. 1997). It is believed that an interaction between wave and particle via cyclotron resonance is responsible for the pitch angle diffusion (Kennel and Petschek 1966) although its exact nature and time dependence is unkown. Diffuse proton auroras can also be produced by the pitch angle diffusion. The two main type of acceleration processes are:

1. Alfven acceleration: Electrons get accelerated by electric field existing in Alfven waves. As a result of this electrons acquires a wide range of energies thus producing short-lived and dynamic auroral forms (Lysak and Lotko 1996).
2. Quasistatic acceleration: electrons are accelerated by a parallel potential drop producing an inverted – V distribution. Electrons acquire a nearly constant energy and the auroras produced in the form of narrow arcs which are aligned in east-west direction (McFadden et al. 1998).

A double layer is defined as “consisting of two equal but oppositely charged space charge layers”. Double layers are plasma structures for which MHD approximation are not valid. They are important for auroral acceleration. A strong parallel electric field of the order of 100-200 V/m exists in these double layers. The auroral arcs have a fine structure of the order of 100m, this fine structure is related to Alfvenic acceleration process. Instabilities stimulated by Alfven waves produces waves having frequencies near the ions gyro frequency or ions may be directly accelerated by them. A parallel electric field exists in dispersive Alfven waves.

Recent Developments

In addition to Kelvin Helmholtz instability other mechanisms for generating the small scale auroral forms is an active research area (Dahlgren et al. 2010). THEMIS all sky imager is used to determine the order of events leading to the onset of substorm (Mende et al. 2011). Studies have shown the presence of a preexisitng auroral arc prior to the substorm onset (Jiang et al. 2012). The expansion phase of the auroral substorm have been studied using the electric current approach (Akasofu 2017).

Recent studies have verified various mechanism of auroral formations by combining the ground based and in-situ satellite measurements (Colpitts et al. 2013). Van Allen probes could provide new data about the processes involved in the formation of diffuse aurora (Fennell et al. 2014). Studies

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investigating correlation between diffuse auroras and dayside whistler mode waves have also been performed (Nishimura et al. 2013). The exact mechanism of quasistatic acceleration is still an open question although it has been studied extensively over past few decades.

Machine learning methods are being used to develop models of the auroral oval based on the Kp index (Feng et al. 2025). Auroral forecast models is an active area of space weather research (Mooney et al. 2024). Recent studies have also shown that in the main phase of a geomagnetic storms resulting from CIR and ICME events K_p index is more useful in explaining the dynamics of auroral currents than the AE index (Boroev and Vasiliev 2021).

Conclusion

Solar wind is the main source of the aurora. This means that the active region responsible for the geomagnetic storms also follow the 27 days solar rotation which might create another aurora 27 days later. The observations and predictions of various events taking place on sun helps in getting forecast of few days about possible auroral displays. As shown in Fig. 5, 25th solar cycle started in 2020, however the population of sunspots during this period was very low thereby resulting in low solar activity. The decrease in number of sunspots will result in less geomagnetic storm that is a major cause for auroral formation. As shown in Fig. 6, the graph shows that from 2018, the intensity of geomagnetic storm is very less, this is due to less sunspots; 2020 marks few minor geomagnetic storms, this result in low auroral events within the past few years. The lower activity of sun might be because of the modern grand solar minimum. Thus, low solar activity will result in less aurora formation.

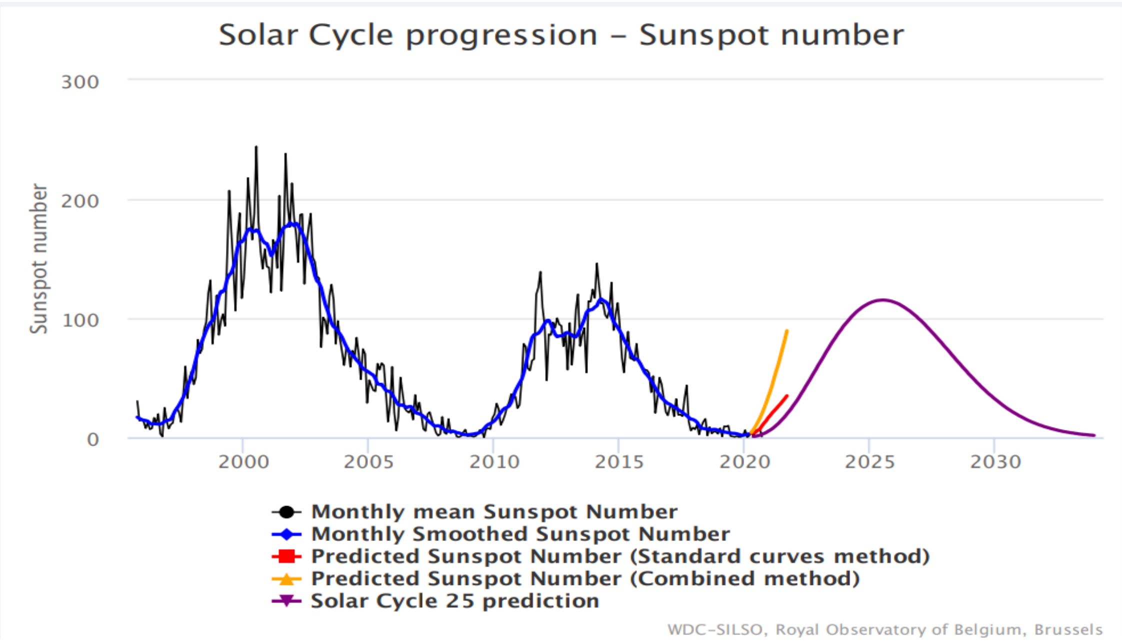

Fig. 5: Graph showing the variations of sunspots (Source : WDC -SILSO, Royal Observatory of Belgium, Brussels).

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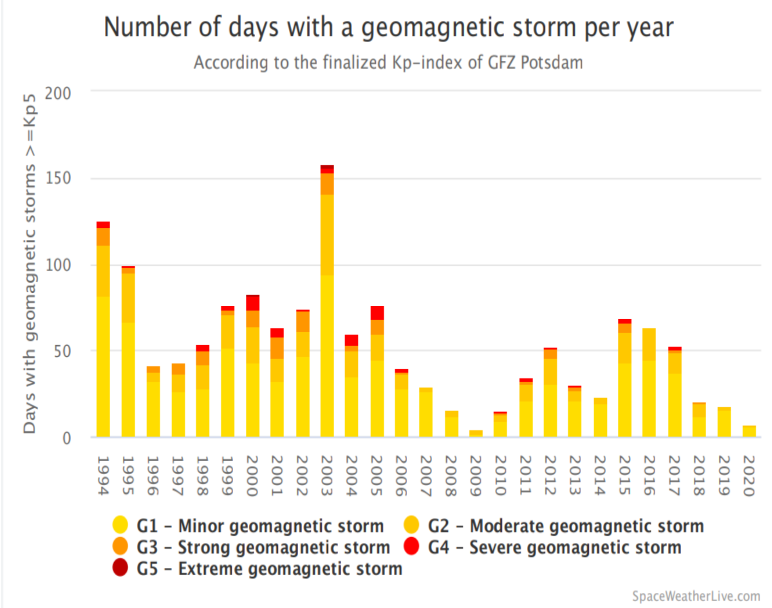

Fig. 6: Graph showing geomagnetic storms leading to auroral formation for the last 25 years (Source: SpaceWeatherLive.Com).

Aurora and accompanying current systems do affect our life on earth's surface. High frequency radio and TV communication often shows strong interference and even complete blackout during auroral displays, or sometimes leading to loss of communication on commercial aircraft heights.

In case of some large events equipment failure cause by induced currents results in large scale power outages. During sub-storms high densities of auroral particles end up in inner magnetosphere, which leads to spacecraft charging and thus failure of such spacecraft. Strong aurora also induces large currents in long telephone lines causing loss of telephonic circuits; power transmission lines are similarly affected. Since aurora induced electric fields, that can increase the rate of ion migration to new arctic pipelines resulting in increased rate of corrosion eventually causing ruptures in pipelines.

Magnetic and particle environment of a planet can be explored using the auroral research. It is possible to determine the location of geomagnetic pole and the temporal evolution of solar activity, if for all the auroras we have 100% accurate observations (Siscoe and Verosub 1986). In recent method ground based observations could be used to determine the characteristics of auroral oval, which eventually provides desired information about solar activity (Wagner et al. 2022).

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