

# Illuminating the Physics of Aurora: A Predictive Model Based on Laboratory Simulations

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**Abstract.** This study aims to simulate the generation of auroras in a laboratory environment and to explore changes in the intensity of artificial auroras under varying physical conditions through mathematical modeling. It introduces the mechanisms behind natural and artificial auroras, explaining the factors influencing auroral intensity. A sufficient data set is obtained by conducting a low-cost, classroom-based experiment while maintaining scientific validity. A predictive model is established using a radial basis function (RBF) neural network, with input parameters including magnetic field strength, current, voltage, vacuum level, electrode distance, and output corresponding to auroral intensity. The model enhances the controllability and accuracy of indoor auroral experiments and provides theoretical guidance for future artificial aurora studies, laying the groundwork for broader space environment simulations.

**Keywords:** artificial aurora, radial basis function network.

## 1. Introduction

Aurora, typically aurora borealis, is a natural light display in the polar region sky. It is a natural phenomenon when high-energy particles of solar wind collide with atmospheric molecules. Nuclear fusion inside the Sun releases large amounts of energy, ionizing gas molecules into plasma to be emitted by the effect of the magnetic field. The movement of the particles is influenced by both the magnetic reconnection and the Lorentz force, directed above the polar regions. Solar particles excite the nitrogen and oxygen in the atmosphere, which produce energy in the form of light when returning to the stable ground state.

As people's understanding of the mechanism of aurora gets deeper, we endeavored to manufacture aurora in a laboratory. Artificial aurora has long been considered important in space physics and plasma physics. It enables scientists to gain deeper insight into the mechanisms of aurora [1] and can also be applied in engineering [2]. Artificial aurora has been successfully simulated in laboratories; however, such experiments typically involve high investment, amounting to €8,000 to €10,000 for equipment, and require high-voltage environments that pose safety risks [3]. Recently, little public data has been available.

This project intends to conduct low-cost, classroom-based artificial aurora experiments by a high school research team. The experiments will ensure data availability for model training, endeavoring to predict the auroral effect based on the equipment's parameters. The model aims to improve the efficiency and controllability of artificial aurora experiments, providing theoretical support for the precise excitation of artificial auroras.

## 2. Mechanism of Artificial Aurora Experiment

In the experimental devices, two electrodes set in a vacuum chamber represent the low-pressure environment of the upper atmosphere. Electrons (solar wind particles) are emitted from the metal sphere (the Sun) connected with the cathode, accelerated by the electric field. When entering the magnetic field area of the magnetic ball (the Earth), high-speed electrons move along the magnetic field lines, guided towards the polar region of the sphere [14]. Particles change their trajectory and collide with gas particles in the chamber. When the breakdown voltage is reached, the gas particles

are excited. They generate light by returning to the ground state. The light produced is the indoor aurora.

### 3. Methodology

We intend to build a mathematical model to predict artificial aurora's potential outcome and possible visual intensity, based on a given set of parameters. A controlled-variable experiment is designed to collect a sufficient and diverse dataset for model construction, training, and testing. It systematically arranges and combines different parameters, including vacuum level, magnetic field strength, voltage, current, and electrode distance, to produce artificial aurora.

#### 3.1 Simulation of Artificial Aurora and Experimental Procedure

The apparatus required for the experiment are: a full-frame camera with high frame rate, a rectangular splicing metal frame with adjustable length, two pieces of long blackout cloth, several plastic pipes and electric wires, two electrodes (cathode and anode), insulated rubber tapes, five 19mm diameter magnetic balls, a 50mm aluminum ball, a D21 series HVDC power supply, an insulating base, a wooden table, a double stage rotary vane vacuum pump, a vacuum chamber, and a stopwatch. The details of the apparatus setup are shown in Figure 1.

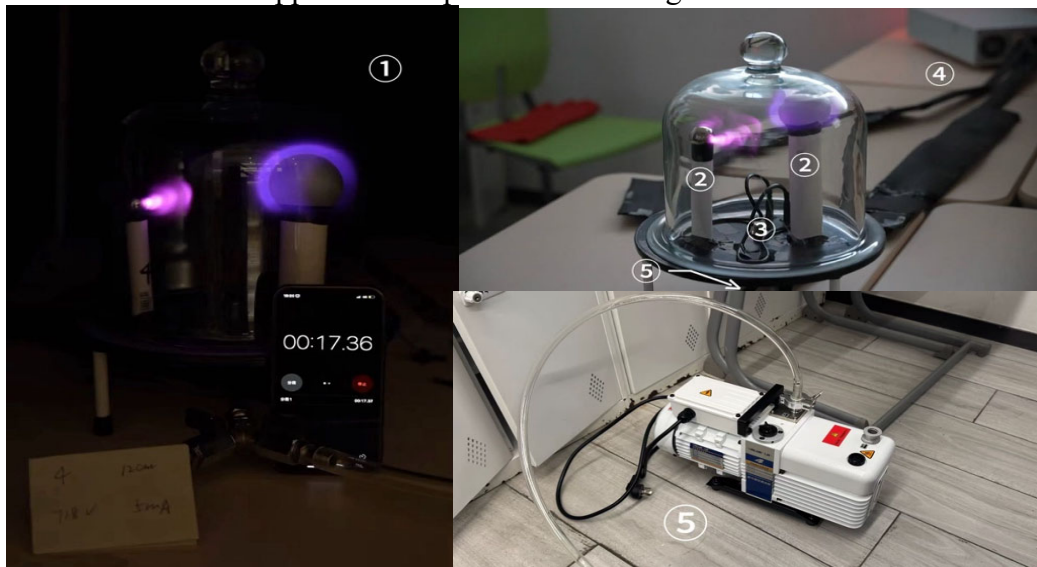


Figure 1. Experiment setup. A dim environment is created by a rectangular adjustable length spliced metal frame and long blackout cloth; the magnetic ball and the aluminum ball are supported by a plastic pipe respectively connected to the anode and cathode by electric wire; the two electrodes—one with a specific magnetic ball and the other with an aluminum ball—are attached to the base using insulated rubber tape; the two electrodes are powered by the D21 series HVDC power supply, creating electron flows. The manually adjustable power supply provides controllable and measurable energy for electron transitions in each round; the vacuum chamber is covered on the insulating base and connected to the double-stage rotary vane vacuum pump. When turning on, a low-pressure environment is created.

#### 3.2 Controlling Variables

Table 1 lists the variables and how they are controlled in the experiment

Variables	Explanation	Effect	Ways of controlling
vacuum level	thinness of air within the vacuum chamber, measured in Pascal.	affecting the possibility of collision between electrons and gas molecules	adjusted by controlling the shut down time of vacuum pump; the visual effect is recorded by the camera.

magnetic field strength	magnetic influence on moving electric charges	determining the movement of charged particles, affecting the stability of plasma.	heating magnetic balls for different amounts of time to change the magnetism; measured by the Gauss meter
voltage	work done per unit charge in electric field	determining the energy of acceleration and the driving force of collision [17]	Settings of the power supply are manually adjusted. Values are displayed on a window.
current	charge passing through per unit time	reflecting the number of electrons in the plasma, the total number of collisions [18].	Settings of the power supply are manually adjusted. Values are displayed on a window.
distance between electrodes	distance between the center of imitated solar wind source and simulated earth model,	determining the energy loss and diffusion degree of the plasma during transmission. [20]	Electrodes are moved to locate at the desired distance based on calibrated scale line drawn.

### 3.3 Data Processing

#### 3.3.1 Image Processing

The original data is in the form of MP4 videos. A frame-by-frame analysis is adopted to measure the intensity of the aurora. Six representative frames are selected for each video by taking QuickTime Player screenshots. Three frames are randomly chosen from the first ten seconds to ensure data volume. The other three correspond to the aurora's appearance at 10s, 20s, and 30s after shutting down the pump, respectively, representing different vacuum levels. This video recording and frame selection strategy allows collecting artificial aurora performance under varying vacuum conditions.

In each image, the aurora appears in a fan shape. Therefore, the visible area of the aurora is selected as the indicator for determining auroral intensity. The longest radius and the maximum angle are measured using geometric analysis software. Area is calculated using the formula.

$$A = \pi r^2 \frac{\theta}{360} \quad (1)$$

#### 3.3.2 Scoring

Assuming that the aurora has a standard sector shape, the scoring process is entirely based on the magnitude of the aurora area. The group with the maximum area is assigned a score of 10, and the one with the smallest area is assigned a score of 0. The scores for the others are calculated as follows:

$$\text{score} = \frac{A_i - A_{\min}}{A_{\max} - A_{\min}} \times 10 \quad (2)$$

Eventually, a data set recording the five parameters and the score of each experiment is obtained and used for the following model training and testing.

### 3.4 Model development

#### 3.4.1 Radial Basis Function Neural Network.

The radial basis function (RBF) neural network is a model that uses a Gaussian radial basis function as its activation function. It consists of three typical layers: an input layer, a hidden layer with neurons, and an output layer. The output is a linear combination of the radial basis functions of the input parameters.

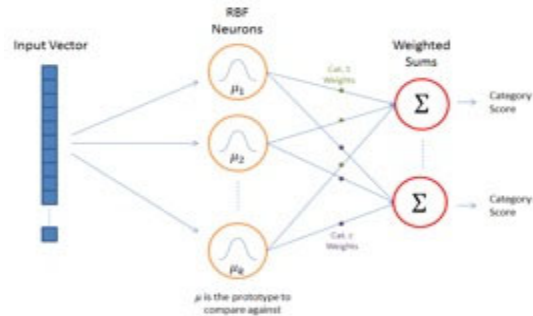


Figure 2: Overview of RBF neural network [31]

This model has strong non-linear fitting ability. It can construct relationships between multiple variables, making it suitable for complex physical problems [25]. It performs well when the investigated variables have non-linear relationships and experimental noise affects the fitting process. However, the approximation capability of the RBF neural network allows it to handle irregular data effectively [26]. Also, its validity is not significantly affected by the amount of data. In other words, it can be trained robustly using a relatively small dataset while maintaining accuracy [27].

### 3.4.2 Training and Testing the Model

The 66 data sets are first ranked in descending order to increase the model's accuracy based on their scores. The ranking shows a negatively skewed pattern, and the lower-ranked data may have relatively high percentage uncertainty, as the area of those auroras is small. As a result, the selection of training and testing sets should include data from all score ranges. The dataset is first divided into a high-score group (top 50%) and a low-score group (bottom 50%). Then, two-thirds of each group are selected as the training sample, while the remaining one-third is used as the testing sample.

A predictive RBF network model is successfully constructed by importing the dataset into MATLAB and using the newrb function.

## 4. Results

### 4.1 Testing results

After training, the model is tested using the remaining one-third of the data.

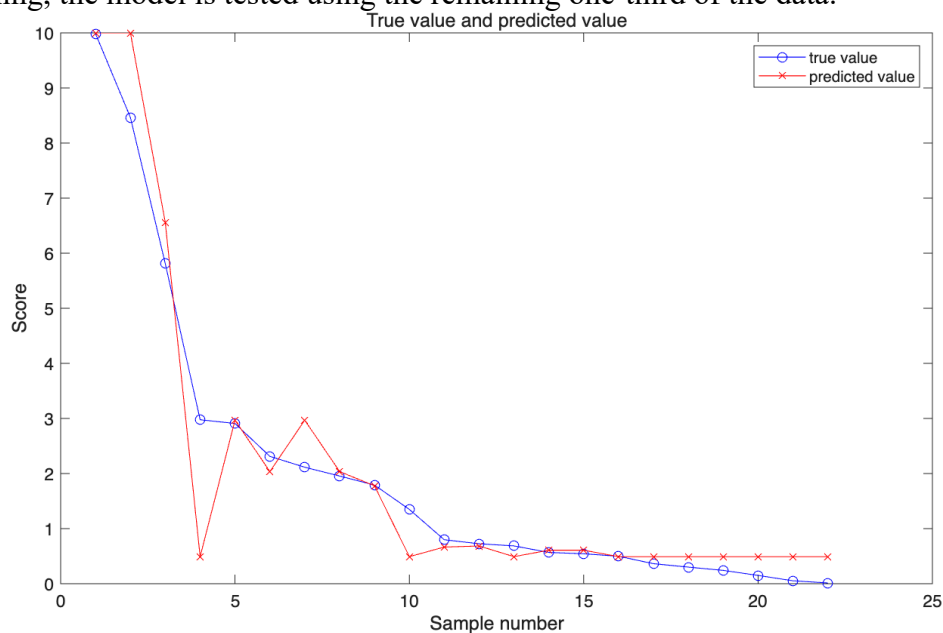


Figure 3. Comparison between predicted value and testing data; x-axis represents the sample number; y-axis represents the score.

In Figure 3, the model's predicted line (red) closely follows the true values of the testing group (blue) from experimental data. The approximation result captures the overall trend well, especially in the high-score region. Although there are small deviations at some points, the mean squared error is only 0.5164, which is quite low and confirms the model's effectiveness.

### 4.2 Effects of Variables on Score

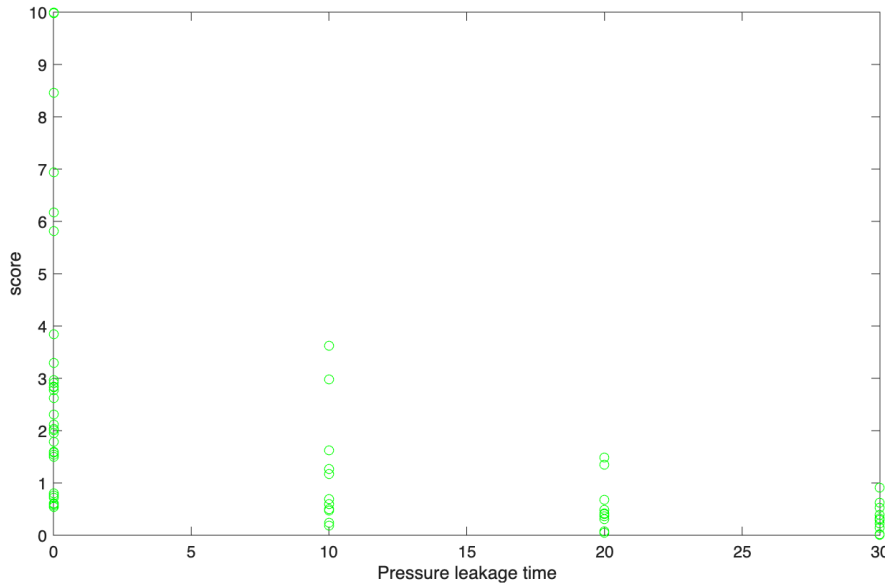


Figure 4. Scatter plot of score against leakage time, assuming the leakage time is inversely proportional to the vacuum level inside the chamber.

Figure 4 shows the distribution of scores under different vacuum levels. Along the x-axis, leakage time increases, so the vacuum level decreases. High-score samples are concentrated around 0 seconds, while low-score samples appear at 30 seconds. This indicates that the auroral effect weakens significantly when air enters the chamber.

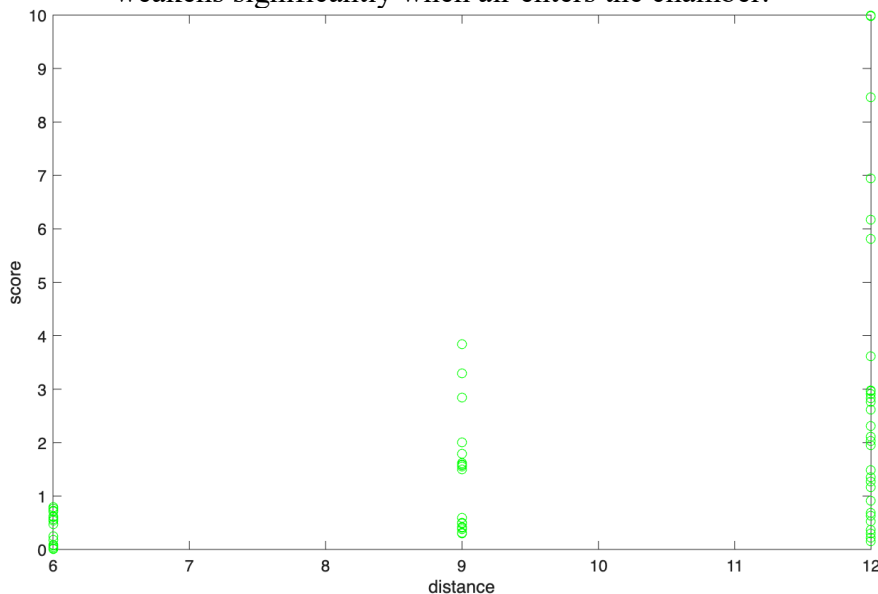


Figure 5. Scatter plot of score against distance between electrodes.

Figure 5 shows the relationship between score and the distance between the magnetic ball (Earth) and the aluminum ball (Sun). High-score samples are mostly at a distance of about 12 cm, while lower scores are found near 6 cm. Overall, the score tends to rise as the distance increases, suggesting that distance plays an important role in shaping the auroral effect.

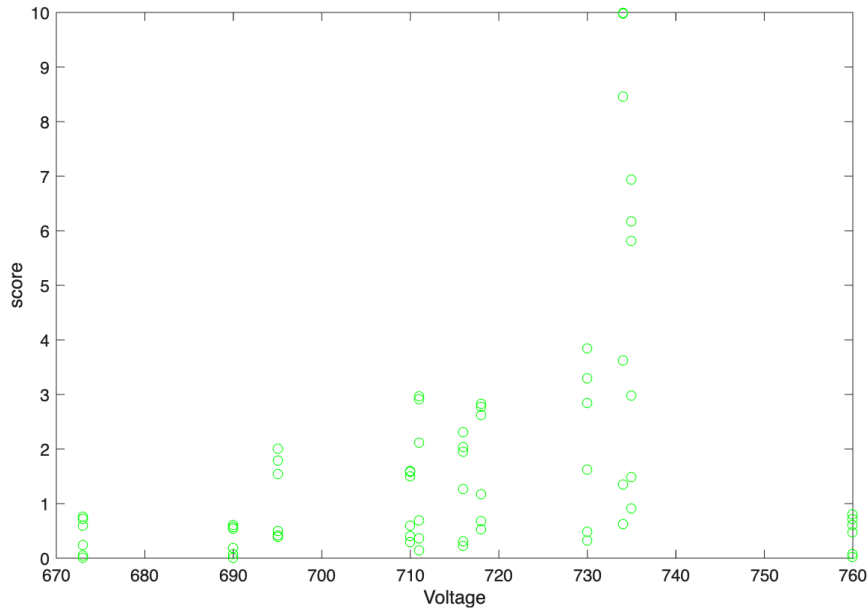


Figure 6. Scatter plot of score against voltage

Figure 6 shows the score against voltage. The points are spread out and not very concentrated. This means voltage still influences the results, but the effect is weaker than factors like distance or vacuum. The relationship is not as clear as in other figures.

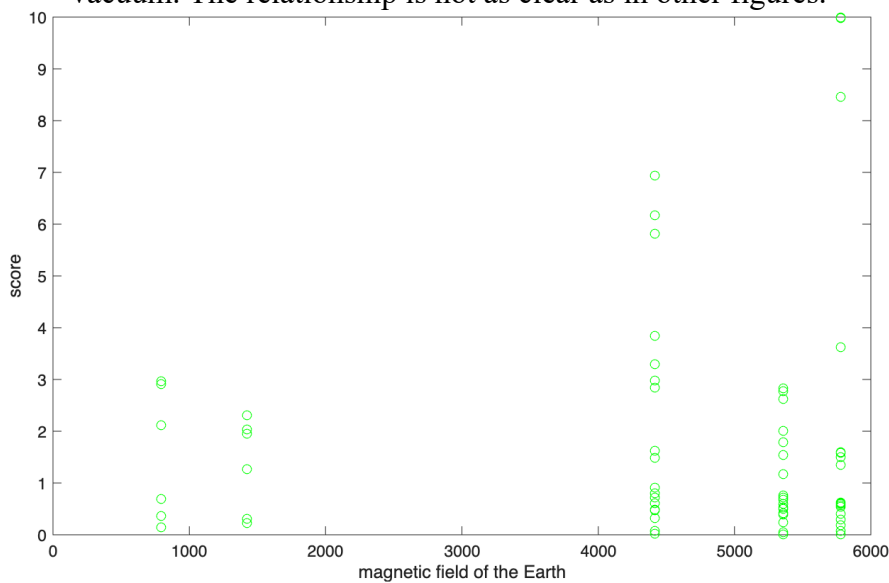


Figure 7. Scatter plot of score against magnetic field strength

Figure 7 shows the relation between score and magnetic field strength. The points are scattered and do not show a strong pattern. This suggests that the magnetic field, current, and voltage have a smaller influence on the aurora intensity. Other factors, such as vacuum level and distance, are more important for the outcome

## 5. Discussion

### 5.1 Strength of the Model

#### 5.1.1 Degree of Model Fitness

The neural network model best fits predicted values and experimental results. The mean squared error is low, and the expected curve closely follows the real data, proving the model's accuracy. Compared with traditional fitting methods, the neural network can deal more effectively with non-

linear relationships among variables. This confirms that the model is simple, efficient, and reliable for predicting aurora intensity.

### 5.1.2 Accuracy

MSE (mean square error) measures predicted and true values. It quantifies the error by calculating the variance [28].

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n (y_i - \bar{y}_i)^2$$

The squared errors will amplify samples with large deviations, making the model pay more attention to large errors. The smaller the MSE, the more accurate the prediction [29]. In this case, the MSE error is 0.5164. Since the range of the experimental data is [0,10], the model's accuracy is demonstrated.

Mean Squared Error (MSE) is used to evaluate the difference between predicted and observed values. In this study, the MSE of the model is 0.5164, which is relatively low given that the experimental score range is [0, 10]. This indicates that the model achieves satisfactory accuracy in predicting auroral intensity. Despite its simplicity, the neural network provides an effective and efficient approach that delivers reliable predictions with limited data. The outcome demonstrates that the model constitutes a valuable study result, offering a practical tool for experimental evaluation and theoretical analysis of artificial auroras.

## 5.2 Influence of Parameters

The experiment also analyzed how different parameters affect the aurora score.

The results show that the distance between electrodes has the most significant influence, with higher scores at around 6 cm and 12 cm. Generally, the score tends to increase with distance, suggesting that distance is a key factor in determining aurora intensity. Vacuum stability also plays an important role, as longer leakage time (lower vacuum) reduces the aurora score, indicating that maintaining a stable vacuum is necessary for producing clear aurora structures. Voltage shows some effect, but the data points are more scattered, meaning that voltage influences aurora formation but not as strongly as distance or vacuum. Magnetic field strength and current have the weakest influence on this experiment, with scores spread out and no strong trend, suggesting that within the tested range, their impact is limited compared to other factors.

Overall, the analysis shows that distance and vacuum level are the most important parameters in this setup. At the same time, voltage has a moderate effect, and magnetic field strength and current have minor effects. This helps explain why the aurora structure and intensity vary under different conditions.

## 5.3 Limitations

### 5.3.1 Distance

Due to the vacuum chamber's limited space, the adjustable distance between the magnetic and aluminum spheres was restricted. This made it impossible to cover the full range predicted by theory, where intensity should rise and fall. Therefore, the downward trend was not observed.

### 5.3.2 Intensity Area

In the experiments, either using the magnetic spheres with the weakest magnetic field strength or setting a small distance between the magnetic ball and the aluminum ball, the observed aurora shape deviated significantly from the expected fan-shaped structure (as shown in Figure 6). In these cases, the insufficient magnetic field constraint prevents the charged particles from forming a typical aurora structure. The aurora appears locally divergent or irregularly diffused, lacking clear boundaries and symmetry. The intensity area could not be quantitatively measured.



Figure 8. An example of the irregular shape of an aurora

### 5.3.3 Vacuum Level

The rate of air leakage may not be linear. Due to the different molecular weights, viscosities, and pump speed responses of the gases, the leakage efficiency of each gas under low pressure varies [30]. This non-linear rise in vacuum level may cause the actual gas composition to be inconsistent with the preset model (ratio of different types of gases in air), affecting the spectral intensity and distribution accuracy. Therefore, assuming the vacuum level is inversely proportional to the time of shutting down the air pump results in an error in estimating the aurora intensity.

## 6. Conclusion

This project built a mathematical model to predict the visual effect of stimulated artificial aurora. A radial basis function neural network was trained with two-thirds of the collected data and tested with the remaining one-third. The results showed that the model predictions followed the experimental trend closely, with a low mean squared error, confirming the accuracy and reliability of the model. In addition, the effects of key parameters, including vacuum level, magnetic field strength, voltage, current, and distance between electrodes, were analyzed. These results show that the model is simple, effective, and valuable for predicting aurora intensity under laboratory conditions.

At the same time, the study also reveals several limitations. The experimental range of variables was restricted by the vacuum chamber size and the magnetic field strength, which limited the observable patterns. Future work can improve the model by expanding the dataset, directly measuring aurora intensity with a spectrometer, and testing a wider range of conditions. With these improvements, the model could provide stronger theoretical support and more practical guidance for future experiments on artificial aurora.

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