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Research on Artificial Aurora: Generation Mechanism, Technology and Application

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Abstract. Natural auroras are luminous plasma phenomena produced by collisions between solar wind charged particles and Earth's magnetosphere, while artificial auroras refer to controllable luminous phenomena simulated by human plasma technology. This paper sorts out three mainstream artificial aurora generation technologies: ionospheric heating, satellite electron beam injection and near-space plasma release. The study adopts case analysis and comparative analysis to compare the luminous scale, energy consumption and operation difficulty of the three technical routes, and systematically analyzes the scientific and engineering application values of artificial auroras, as well as potential ionospheric disturbance risks. The results show that ionospheric high-frequency heating is the most mature scheme for large-area artificial aurora with low energy cost but limited brightness; electron beam injection can form high-brightness aurora but has high launch cost; plasma balloon technology is low-cost and easy to implement yet only generates short-lived small-scale aurora. This research supplements horizontal comparative data of multiple artificial aurora technologies and provides reference for low-interference artificial aurora experiment design.

Keywords: Artificial Aurora, Ionospheric Heating, Plasma Luminescence, Space Physics, Magnetosphere Simulation

1. Introduction

Auroras have been documented by numerous civilizations since ancient times. In 1619, Galileo named the Aurora Borealis. Centuries of studies confirm natural auroras form as solar wind charged particles precipitate along geomagnetic field lines and collide with upper atmospheric particles to emit light. To verify the auroral particle transport theory, scientists conceived artificial aurora experiments, which inject controllable high-energy electron beams along magnetic field lines to reproduce auroral luminescence. In 1969, NASA launched an electron accelerator-equipped sounding rocket from Wallops Island. A monoenergetic electron beam was injected downward along geomagnetic field lines, generating detectable artificial auroras within the ionosphere [1]. This pioneering test first verified the feasibility of artificial aurora generation. It established a novel approach to investigate the magnetosphere, magnetic field lines and auroral physics via artificial particle beams, laying a vital experimental basis for further studies of space plasmas and auroral particle acceleration.

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This paper consists of three core sections: explaining the physical luminescence principle and sorting technical routes, comparing three mainstream artificial aurora technologies with global experimental cases, and discussing multi-scenario applications alongside standardized proposals to mitigate ionospheric disturbances. Adopting case studies, comparative analysis and space plasma theoretical deduction. This work fills the gap in systematic cross-technology comparison in this field and provides optimization strategies for artificial aurora experiments.

2. The basic physical mechanism of artificial aurora

Based on space physics theory, the ionosphere's unique conductive properties form closed conductive pathways for large-scale Birkeland field-aligned currents. Parallel electric fields distributed along geomagnetic flux tubes act as the key acceleration source that accelerate magnetospheric electrons to high energies. After acceleration, these energetic electrons sink into the upper thermosphere and collide with neutral atomic oxygen and nitrogen, producing the characteristic auroral emissions. In addition, Alfvén waves and diverse wave-particle interactions modulate the large-scale shape and tiny fine structures of auroral forms, constructing a full picture of magnetosphere-ionosphere energy transport. These well-established physical mechanisms not only explain the formation of natural auroras, but also lay a solid theoretical foundation for designing artificial aurora experiments. To physically reproduce and validate this particle acceleration and atmospheric luminescence process, the following sections will detail the technical architecture of rocket-borne monoenergetic electron beam missions and analyze corresponding artificial aurora observational results [2].

3. Main technical approaches for artificial aurora generation

3.1. Approach to generating artificial aurora via controlled electron beams on sounding rockets

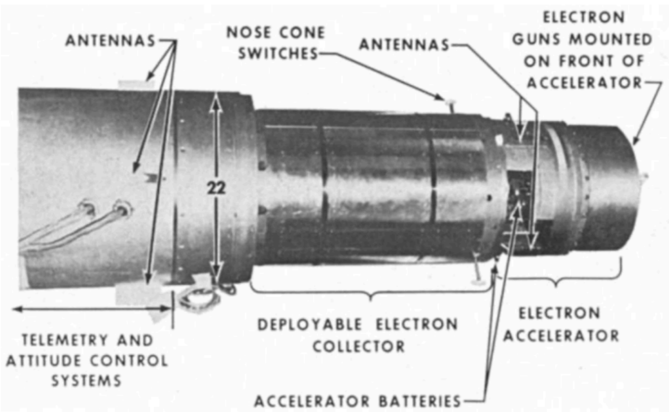

Figure 1. Schematic diagram of the Aerobee 350 sounding rocket payload configuration for the 1969 Wallops Island artificial aurora experiment

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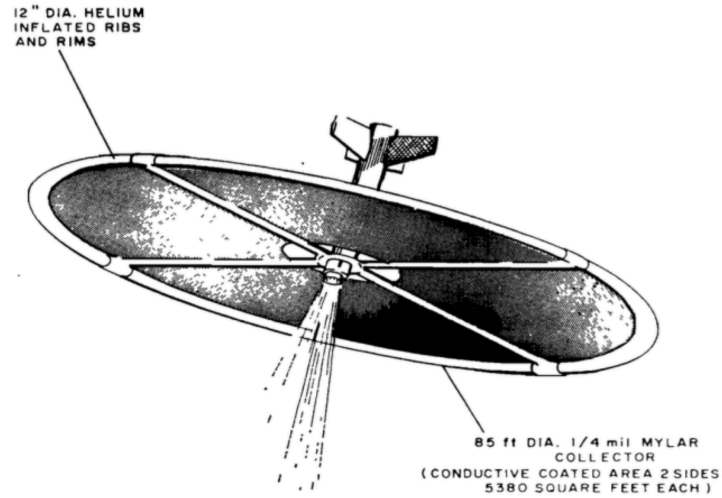

Fig. 7. **The collector screen in the deployed configuration used to collect current to keep the rocket near electrical nutrality.**

Figure 2. Schematic diagram of the deployable electron collector screen carried by the Aerobee 350 sounding rocket for the 1969 Wallops Island artificial aurora experiment [1]

Figure 1 shows the key components of the sounding rocket payload, including the electron accelerator fitted with electron guns at the front, deployable electron collector, antennas, nose cone switches, telemetry and attitude control systems, which work cooperatively to inject monoenergetic electron beams downward along geomagnetic field lines for generating artificial auroras.

Figure 2 illustrates the fully deployed conductive Mylar collector screen supported by helium-inflated ribs and rims, which captures free electrons in the ionosphere to offset rocket positive charging and maintain the vehicle's electrical neutrality during electron beam emission.

As one classic technical route to generate artificial auroras, the sounding rocket-carried controlled monoenergetic electron beam scheme was fully verified in the 1969 Wallops Island experiment recorded by Hess et al. [1]. This technical system relies on an Aerobee 350 sounding rocket carrying a compact high-power electron accelerator as the core payload. Equipped with ten sealed electron guns, the accelerator can output tunable electron beams ranging from 1.25 kV to 9.5 kV with a maximum beam current of 490 mA, forming periodic pulse signals to inject charged particles downward along geomagnetic field lines. To eliminate severe spacecraft charging caused by continuous electron emission, a 26-meter aluminized mylar foil was designed and deployed perpendicular to magnetic field lines to collect return ionospheric electrons and balance the vehicle potential. Ground multi-spectral optical cameras were arranged to capture luminescence signals produced by the collision between descending high-energy electrons and upper atmospheric oxygen and nitrogen molecules. Experimental observations confirmed that the injected electron beams could propagate nearly 200 km along magnetic lines without being dissipated by severe plasma instabilities, creating detectable artificial auroral rays at an altitude of approximately 104 km, which proves the technical feasibility of using controllable rocket electron beams to simulate natural auroral precipitation processes [1].

NASA's 1969 Wallops artificial aurora experiment relied on high-power onboard electron guns to shoot monoenergetic electron beams along geomagnetic field lines and produce artificial auroral rays. This scheme had critical drawbacks: heavy power loads limited aurora brightness, beam-plasma two-stream instabilities caused severe energy loss along long field lines, and the scheme

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only reproduced terminal auroral emission without natural magnetosphere-ionosphere coupling processes.

Recent multi-satellite observations [3] reveal that natural discrete auroras are powered by Alfvén waves. Shear and kinetic Alfvén waves transport electromagnetic Poynting flux from the magnetotail to the auroral acceleration region, dissipating energy to form quasi-static parallel potential drops described by Vlasov-Poisson equations. These potentials bidirectionally accelerate precipitating electrons and escaping O^+ ions with a 59% total energy conversion efficiency.

An Alfvén wave-assisted artificial aurora design solves the earlier experiment's defects. Plasma cloud releases or magnetic coils generate Alfvén waves to supply most accelerating energy; only low-power seed electrons are injected. The self-formed potential drop creates classic inverted-V monoenergetic auroras, while kinetic Alfvén waves can produce diffuse auroras. This lightweight setup suppresses beam instabilities, fully reproduces natural auroral energy cascades, and enables measurements of field line topology, ionospheric composition and cross-planetary auroral comparisons. Further work is needed to precisely control Alfvén flux and quantify wave dissipation across geomagnetic environments [3].

3.2. Auroral simulation via gas discharge tubes

Laboratory gas discharge tubes provide a low-cost, compact analog to reproduce the optical emission of natural auroras, governed by Townsend discharge theory (under an applied electric field, primary electrons collide with neutral gas molecules and trigger α ionization to form electron avalanches). Positive ions drift toward the cathode and generate new seed electrons via γ secondary emission. Once the self-sustaining discharge criterion is satisfied, low-pressure gas maintains steady glow. Excited oxygen and nitrogen atoms emit visible light, resembling auroral radiation. This whole process is fully interpreted by Townsend discharge theory, which only works for low-pressure, short-gap plasma systems [4].

Two core Townsend mechanisms sustain stable plasma glow inside the tube: the primary α ionization creates electron avalanches as accelerated electrons collide with low-pressure oxygen and nitrogen molecules, while the secondary γ emission replenishes seed electrons via ion bombardment on the cathode, enabling self-sustained luminescence without continuous external excitation. This miniature plasma setup mimics the collision radiation process occurring when energetic electrons precipitate into Earth's ionosphere, which is the fundamental source of auroral light. However, the pure electrostatic discharge model lacks the magnetized Alfvén waves and large-scale quasi-static potential drops that dominate real magnetosphere-ionosphere coupling. Combined with an external magnetic coil to simulate geomagnetic fields and controlled wave excitation to replicate Alfvén wave energy input, the discharge tube platform can be upgraded to validate the Alfvén-wave-powered auroral acceleration mechanism summarized by Tian et al. [3]. Unlike NASA's high-power electron beam rocket experiments [1], this bench-top simulator avoids complex spaceborne hardware and offers repeatable, adjustable conditions to observe inverted-V-like monoenergetic particle signatures and plasma emission spectra for comparative auroral research.

However, this method is only used for indoor physical verification. The system consists of a sealed vacuum tube filled with low-pressure oxygen-nitrogen mixed gas and an internal permanent magnet simulating the geomagnetic dipole field. High-voltage electrodes emit electron flows inside the cavity; charged particles spiral along artificial magnetic lines and collide with gas molecules to produce aurora-like glow with consistent spectral characteristics of natural auroras. Dating back to Birkeland's famous terrella experiment, gas discharge devices can visually reproduce the basic luminous mechanism of auroras at low cost. However, it cannot create actual artificial aurora in the

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80-150 km upper atmosphere, nor support magnetosphere field detection or ionosphere parameter measurement, so it only serves as a basic teaching and theoretical simulation tool rather than an on-orbit experimental technology.

3.3. Ground-based high-frequency radio wave heating technology for artificial aurora

As illustrated in Figure 3， represented by the HAARP 3.6 MW high-power transmitting array, this ground-based technique generates artificial auroras without rocket platforms. It emits directional HF radio waves tuned to the second electron gyrofrequency at around 220 km, transferring energy to ionospheric plasma via electron cyclotron resonance and producing suprathermal electrons. Collisions between energetic electrons and atmospheric oxygen and nitrogen atoms excite typical auroral emissions at 630.0 nm, 557.7 nm and 427.8 nm, forming visible artificial glows.

In full-power heating tests, sustained HF irradiation creates an artificial dense plasma layer at the bottom of the F-region near 200 km [5], where electron density is six times the background level at the same altitude. This localized density enhancement refracts incoming radio beams: rays with zenith angles of 4°-12° deflect outward and gather into an annular high-energy zone, while concentrated power at the beam center forms a bright core, jointly producing a unique bullseye auroral pattern with a central disk and outer luminous ring. Multi-site optical cameras, ionosondes and GPS TEC receivers are applied synchronously to capture auroral morphology, vertical plasma profiles and electron content perturbations, verifying artificial ionization.

Ray-tracing simulations accurately reproduce the ring-shaped glow based on measured ionospheric density data. Energy budget calculations confirm that suprathermal electron impact ionization dominates plasma and light production, consuming less than 10% of the transmitter's total power. Estimated ionization rates derived from 427.8 nm blue emission match theoretical predictions well.

This method supports long-duration, repeatable parameter adjustment, yet it only produces diffuse annular or spotted auroras rather than thin discrete natural auroral rays with relatively low brightness. The bullseye optical feature serves as an intuitive visual marker to reflect the scope and strength of artificial ionization within the radio beam, offering a reliable observation standard for ionospheric modification and artificial aurora research.

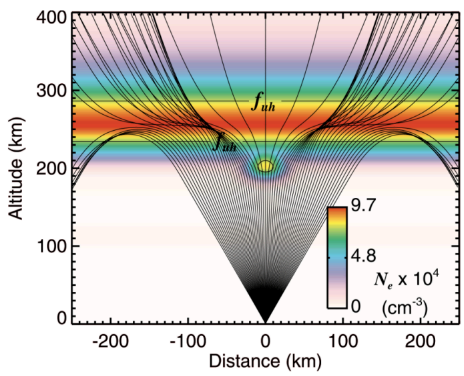

Figure 3. Bullseye-shaped artificial aurora induced by HAARP high-frequency ionospheric heating [5]

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4. Conclusion

This paper systematically elaborates the physical luminescence mechanism of artificial auroras and three mainstream generation technologies: rocket-carried electron beam injection, laboratory gas discharge tube simulation, and ground-based HF ionospheric heating. Based on global experimental cases such as NASA's 1969 rocket test and HAARP heating observations, the paper compares the three approaches in luminous range, energy cost, implementation difficulty and applicable scenarios.

The analysis shows that HAARP-type ground heating is the most mature scheme for large-scale artificial auroras, supporting long-term, repeatable observation experiments without rocket launches. Rocket electron beams create high-precision, bright auroral rays close to natural auroras, yet expensive launch and power costs limit wide application. Gas discharge simulation costs little and operates easily, but only realizes indoor spectral simulation; similar plasma release methods produce auroras lasting mere minutesand are only suitable for short-term mechanism verification.

In addition, all artificial aurora experiments bring temporary regional ionospheric disturbances, which will interfere with ground shortwave communication. This paper further puts forward standardized experimental suggestions to mitigate such adverse impacts.

The limitation of this paper is that it only carries out qualitative analysis based on existing experimental data, without quantitative numerical simulation results of long-term ionospheric perturbation. Subsequent research can adopt plasma simulation software to quantify the ionospheric disturbance range triggered by artificial auroras of different sizes, and develop low-energy, low-interference luminescence schemes to realize precisely controllable artificial aurora experiments.

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