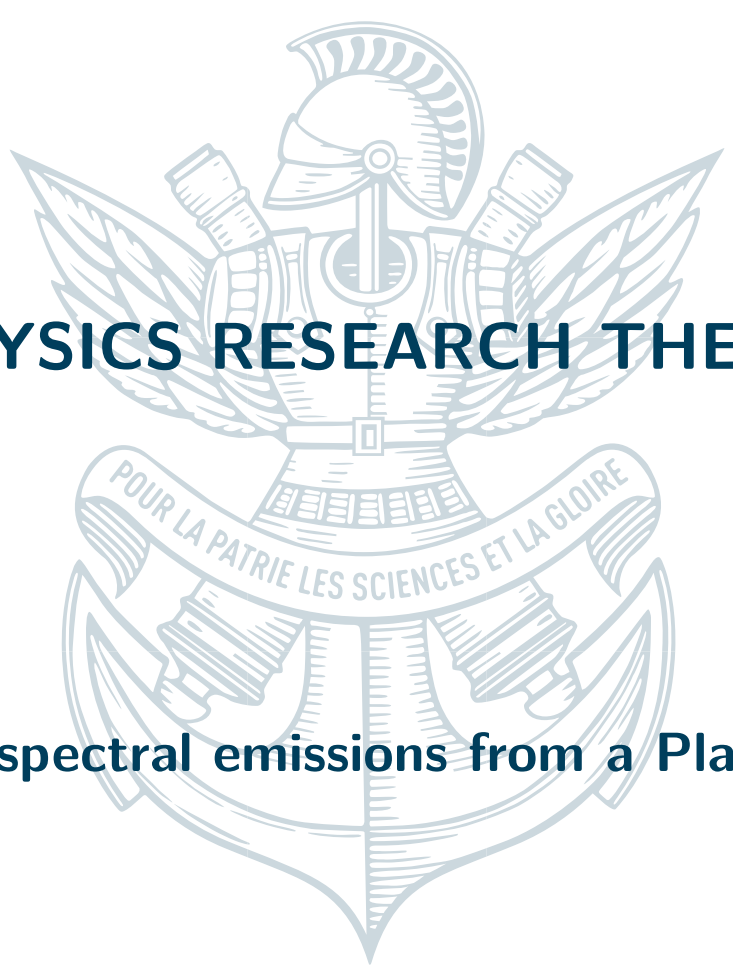




PHYSICS RESEARCH THESIS

Study of spectral emissions from a Planeterrella

17th August 2026

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Supervised by Dr. Rowan Dayton-Oxland



UNIS
The University Centre in Svalbard

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Acknowledgment

There are many people I would like to express my gratitude to for having made my research thesis significantly more enjoyable or even possible in the first place.

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Chapter 1

Introduction

The Planeterrella is a laboratory analogue of the Earth’s magnetosphere system. Initially designed as a pedagogical tool, it is also well suited to more quantitative study. Its emitted light, like that of the real aurora, contains information about the underlying plasma physics through its spectral content.

This thesis reports on a four-month project at the University Centre in Svalbard (UNIS), combining experimental spectroscopy of the newly acquired UNIS Planeterrella with a numerical particle-tracing model of its electron population. Experimentally, the goal was to obtain calibrated optical spectra of the Planeterrella’s canonical configurations and more, to provide information for the next users.

Following the receipt of code from Mathieu Barthélemy in June, a parallel objective was added: to extend an existing MATLAB electron-trajectory model into a more flexible, accurate, and efficient Python implementation.

These two strands informed one another throughout: asymmetries in the auroral oval configuration were reproduced and explained through simulated trajectories, the electron confinement of the stellar ring configuration was quantified via collision statistics, and a previously unexplained blue glow was traced spectroscopically to a candidate physical origin distinct from the plasma emission itself.

The thesis proceeds as follows. Chapter 2 covers the theoretical background: atomic and molecular collisional excitation, and the specific physics and canonical configurations of the Planeterrella. Chapter 3 describes the experimental setup and its wavelength and flat-field calibrations. Chapter 4 presents the numerical model and simulation results. Chapter 5 presents the experimental spectra, including the discovery of the blue continuum emission.

1.1 AURORA IN SVALBARD

The aurora, most commonly known as the northern or southern lights, is one of the most visually striking manifestations of the interaction between the Sun and the Earth’s space environment. Even though this phenomenon has been observed for centuries and scientifically explored since Galileo in the early seventeenth century, no universally accepted definition of the aurora exists. For the purpose of this work, I will use the definition provided by my supervisor Rowan Dayton-Oxland [10]. The aurora will be defined as natural light emissions caused by particles energized by magnetospheric processes interacting with the upper atmosphere. This definition is broad enough to include virtually all auroral phenomena, including the more exotic, recently discovered GHOST and STEVE auroras.

Beyond their visual appeal, the aurora is a window into the physical state of the upper atmosphere and the particles that generate it. Because the light emitted by the aurora is made out of a set of discrete emission lines, it is possible to use spectrometry to identify the emitting chemical species and get diagnostic information about the state of the plasma.

The geographic location of Svalbard makes it particularly well-suited for auroral research. Located at 78° N, the main city Longyearbyen is beyond the typical auroral location (60 - 75° roughly), meaning it doesn’t experience the more energetic auroras that occur at lower latitudes. Instead, this location, deep into the polar circle, allows for the investigation of auroral phenomena happening on the dayside of the planet, which are difficult to observe from lower-latitude sites. The Kjell Henriksen Observatory (KHO), located near Longyearbyen, takes advantage of this geographic position. The observatory hosts a range of optical instruments dedicated to investigating auroral and ionospheric phenomena [17]. Its location enables continuous and long-duration observations of the polar upper atmosphere.

One example of active research at the KHO is the study of GHOST (Geomagnetically-driven High-bandwidth Optical Spectrum from Thermosphere) aurora [26], a new auroral form. Unlike the classic discrete green and red auroral lines, GHOST auroras appear as off-white, gray, or pale pink broadband continuum glowing structures that move alongside standard auroral structures. Researchers have linked these continuum emissions to intense thermospheric plasma heating and hot molecular nitrogen (N_2) within the dayside polar cusp [10].

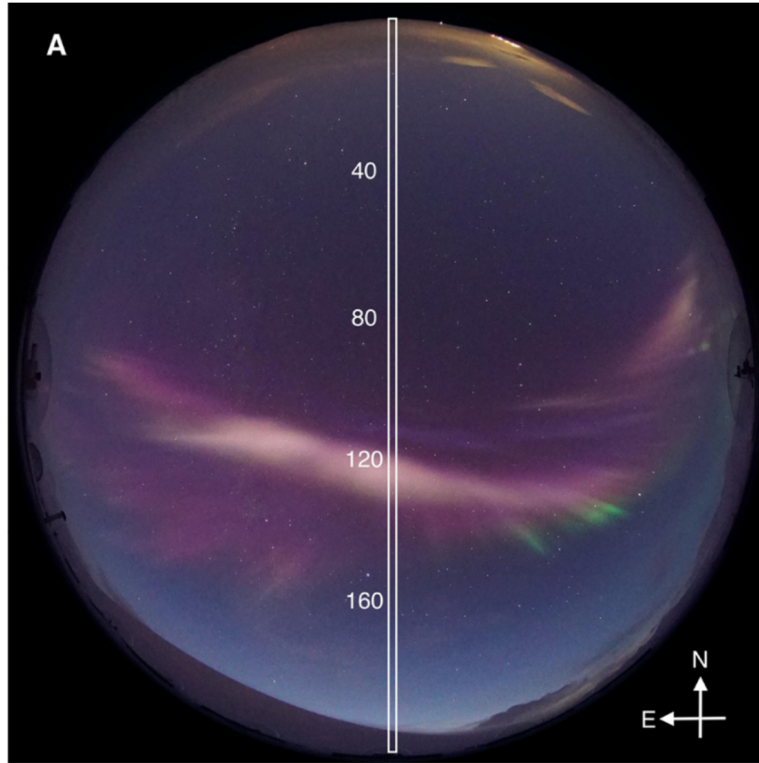


Figure 1.1: Image of a day-side aurora taken from the KHO, taken 3 January 2020 8:48:56 UT from [27]. The white aurora, which could be mistaken for a cloud, is a GHST aurora.

1.2 THE PLANETERRELLA

The Planeterrella originates from the Terrella ("little Earth") experiment performed by the Norwegian scientist Kristian Birkeland in the early 20th century. The Terrella consisted of a magnetized sphere sealed in a vacuum chamber and bombarded with a beam of electrons. The Planeterrella is a scaled-up version of this experiment, designed to study the physics of auroral phenomena in a laboratory setting. This setup leads to the creation of luminous rings around the sphere's magnetic poles, which Birkeland correctly interpreted as similar to the auroras, leading to the discovery of field-aligned currents connecting the aurora to the magnetosphere (now called Birkeland currents).

The modern Planeterrella, developed by Jean Lilensten in the early 2000s and still being improved today, is a direct descendant of Birkeland's Terrella. The experiment has been modified to be safer, more versatile, and easier to operate. These changes stem from a paradigm shift, where the Planeterrella is now used as a pedagogical tool to teach the physics of auroras, rather than a research tool to study them. The Planeterrella has been used in many countries and has been shown to be an effective way to engage students and the public in the science of auroras. Indeed, a public demonstration of the Planeterrella is often the only way for the

general public to see what an aurora would look like. Because this new design is education-oriented, the blueprint requires cheaper materials and results in a compact and transportable device. Planeterrellas are regularly demonstrated by university observatories and outreach associations, including at the Observatoire des Sciences de l'Univers de Grenoble and educational associations such as AurorAlpes, which use the setup for aurora science communication.

This redesign of the Terrella still retains the essential mechanisms of the original experiment. Two spherical magnetised electrodes are placed in a vacuum chamber, and a high voltage is applied between them to create a plasma discharge. In its typical configuration, the device produces a characteristic purple and pink glow around the two electrodes, which is the result of the interaction between the electrons and the nitrogen molecules present in the rarefied air. With the right settings, the glow can form a ring reproducing the auroral ovals, or more complex structures such as the solar corona or Van Allen belts. However, it is crucial to keep in mind that the observed phenomena can't reflect the full complexity of the real physical processes. Some may look similar for the wrong reasons, some may look different for the right reasons. The Planeterrella is a simplified model of the aurora, and it is not meant to be a perfect replica of the real phenomenon. It is a tool to help us understand the physics behind the aurora and to engage the public in the science of space weather.

Chapter 2

Theoretical background

2.1 ATOMIC AND MOLECULAR EMISSION

This section was written using Dayton-Oxland [10], Aurora by Vallance Jones [16], and Chemical Kinetics by Patel [29] as references. At the microscopic level, the process responsible for all emissions discussed in this paper (real auroras and Planeterra) is inelastic collisional excitation.

Let's consider an electron of kinetic energy E colliding with a species with a discrete set of internal energy levels. This species is able to be excited from an initial state i to a final state f as long as the electron possesses enough energy, i.e. $E \geq \Delta E_{if}$. When the species moves back to a lower energy level, it emits a photon of wavelength $\lambda = \frac{hc}{\Delta E}$. But this says nothing about how likely this process is to occur. This data is provided by the energy-dependent cross-section $\sigma_{if}(E)$, which reaches a maximum for a specific incident energy E , then converges to zero following an inverse power law.

However, for a diatomic target such as N_2 or N_2^+ , the initial and final states do not differ only by their electronic state. With the Born-Oppenheimer approximation, the total internal energy of diatomic molecules can be split into independent electronic, vibrational, and rotational contributions :

$$E_{tot} = E_e + E_v + E_r$$

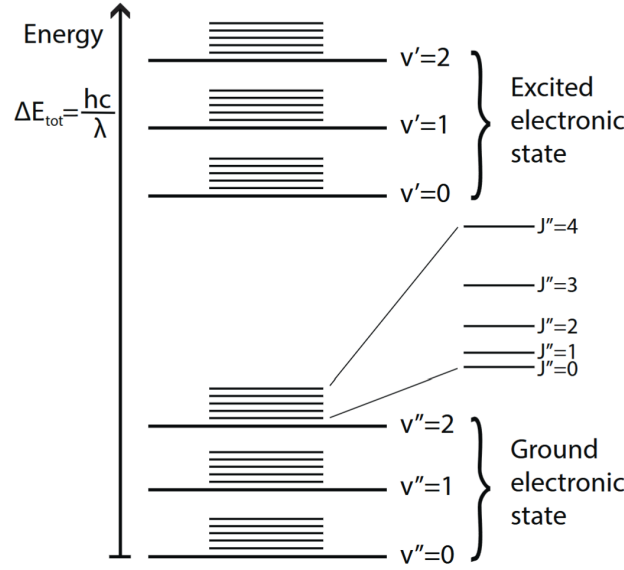


Figure 2.1: Simplified diagram showing electrical, vibrational, and rotational energy states, taken from Holmen[15]

The vibrational levels of a given electronic state are approximately those of a harmonic oscillator, $E_v = h\nu(v + 1/2)$, where h is Planck's constant, ν the vibrational frequency, and $v \in \mathbb{N}_0$ is the vibrational quantum number. The rotational energy is given by $E_r = \frac{h^2}{8\pi^2 I} J(J + 1)$, where $J \in \mathbb{N}_0$ is the rotational quantum number. The basic wave mechanical equations for collisional excitation [16] indicate that the probability of excitation by electron impact between v'' and v' should, to a good approximation, be proportional to the Franck-Condon factor.

$$q_{v'v''} = \left| \int \psi_{v'}(r) \psi_{v''}(r) dr \right|^2$$

With the normalization property that $\sum_{v''} q_{v'v''} = 1$. These factors, rather than the electronic transition moment alone, set the relative intensities within a vibrational progression and hence the comb-like appearance of a molecular band system. Once the upper level v' is populated at number density N'_v , the photon emission rate per unit volume in the $v'v''$ band is :

$$I_{v'v''} = A_{v'v''} N_{v''} h\nu_{v'v''}$$

where $A_{v'v''}$ is the Einstein coefficient for spontaneous emission and the total radiative decay rate of the level, $A_{v'} = \sum_{v''} A_{v'v''} = 1/\tau_{v'}$, defines its radiative lifetime. For example, the N2 Second Positive System $C^3\Pi_u \rightarrow B^3\Pi_g$ has $\tau = 40$ ns, short enough that its population reaches steady state on the timescale of the excitation itself. But radiative decay is not the only process that can depopulate an excited state. Collisional quenching, that is, loss of excitation energy in collisional processes, can depopulate the state before it has a chance to radiate. The

competition between radiative decay and collisional quenching by a third body M, associated with a coefficient $k_q[M]$, leads to the following population balance equation (for the example of the N2 Second Positive System):

$$\frac{dN_C}{dt} = \frac{d}{dt}(\sum_{v'} N_{v'}) = \sum_{v'} (R_{exc,v'} - A_{v'} N_{v'} k_q[M] N_{v'}) = R_{exc} - A_c N_C - k_q[M] N_C$$

whose steady-state solution, $N_C = R_{exc}/(A_c + k_q[M])$, defines an effective radiative quantum yield

$$\eta_C = \frac{A_c}{A_c + k_q[M]} = \frac{1}{1 + k_q[M] \tau_{v'}}$$

Quenching becomes significant once $k_q[M] 1/\tau_{v'}$, i.e. above a critical density $[M]_c = 1/(k_q \tau_{v'})$ set by the state's own lifetime. This is the quantitative reason long-lived forbidden transitions (the O I green and red lines) collapse at the pressures/altitudes where short-lived allowed transitions like the 2PG and 1NG bands are barely affected, and it is the dependence exploited directly in this thesis by comparing Planeterrella spectra at different working pressures.

2.2 PHYSICS OF THE PLANETERRELLA

The section will first consider the basic physics required to understand the Planeterrella, and then discuss the "canonical" configurations of the Planeterrella listed on the OSUG website.

2.2.1 PHYSICS OF THE PHENOMENON

This subsection uses the work of Jean Lilensten [19] and Guillaume Gronoff [5] as sources. The magnetic field in the Planeterrella originates from the magnets placed within the spherical electrodes, one in the small sphere but two in the bigger one, arranged to produce the required bipolar magnetic topology over its larger surface (more sun-like than a dipole). They produce a field of ~ 0.5 T on their surface, much stronger than the Earth's magnetic field but helpful to visualize phenomena at our scale. The potential applied between the electrodes, typically around 1 kV, accelerates the electrons, giving them suprathermal energies of ~ 1 keV ($T_e \gg T_i \approx T_{\text{neutral}}$). These electrons collide with the rarefied air, mostly N2 and O2, and induce ionisation amongst other phenomena. The stationary continuity equation for electrons implies that production and losses of charged particles balance; we can therefore assume quasi-neutrality in the plasma [19]. With this condition, we can approximate the electron density n_e to be around 10^{17} m^{-3} . But the suprathermal electron density n_e^s is smaller than that, typically by a factor of 10,000! This is because the suprathermal electrons repeatedly ionize the neutral

species as they travel. The first ionization energy of N₂ is 16 eV, and with other energy loss processes, a suprathermal electron can generate a few dozen slower electrons with an energy around 1 eV [1], so $T_e = 1.1 \times 10^4$ K. The suprathermal population is also short-lived compared with the lower-energy electron population, as suprathermal electrons rapidly lose energy through collisions with the background gas.

• DEBYE SCREENING

The ions produced by the suprathermal electrons gather near the cathode because of their charge, and create a screen that limits the influence of the cathode electric field. The characteristic screen size is the Debye length :

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e^s e^2}}$$

where n_e^s is the suprathermal electron density. The electrode perturbs the local plasma, causing electrons and ions to redistribute. This space-charge response screens the electrode's electric field over the Debye length. The potential at a distance d from the electrode will then be

$$V = V_0 \exp\left(-\frac{d}{\lambda_D}\right)$$

After several Debye lengths, or ~ 2 mm in our configuration, the potential variation is negligible, and the electric field from the electrodes becomes negligible too. The region close to the cathode appears dark because it is not populated by the ambient electrons, who have a low enough energy to excite the air species and create light outside of this region.

• EXCITATION AND PHOTO EMISSION

From a few millimetres away from the cathode, and because of plasma quasi-neutrality, the electron trajectories are mainly controlled by the magnetic fields and by collisions. The electrons experience a rotation with a cyclotron frequency ω_c and a Larmor radius r_L given by

$$\omega_c = \frac{eB}{m_e}, \quad r_L = \frac{v_\perp}{|\omega_c|}$$

Because the magnetic field from the spheres is dipolar, its magnitude decreases rapidly with distance. The spatial gradient of the dipole introduces a gradient drift (∇B drift) perpendicular to both the magnetic field and to its gradient. This gradient causes the electrons to circulate around the spheres, producing the ring current, but collisions eventually interrupt this process. In the ring current regions, collisions give the circulating electrons some velocity along the magnetic lines. As the magnetic field lines converge close to the poles, the excitation rate per unit area increases, such that the emission intensity increases enough to be visible and creates the auroral ovals.

The visible radiation results from ambient electron-impact excitation of N_2 and O_2 . We can distinguish 3 dominant colours. The blue/violet emission is dominated by the N_2^+ first negative system, whose principal emissions are at 391 nm and 427 nm. The blue emissions originate from the N_2 second-positive system, between 300 nm and 400 nm, with 337.1 nm for the visible part. The red/pink colour also originates from N_2 , but from the first-positive system, mostly between 600 and 800 nm for the visible part. The spatial distribution of the colours reflects the electron energy loss. Energetic electrons near the cathode can ionize the gas, leading to N_2^+ colours, whereas after losing their energy, the plasma remains mostly colourless until the electrons get close to the anode, where they are re-accelerated and emit $N_2 1p$ in the red.

2.2.2 CANONICAL CONFIGURATIONS

[32] The Planeterrella can host many different configurations, leading to a large variety of simulated phenomena. The main configurations are listed on the OSUG website [25], hosted by the Grenoble University and in close contact with Jean Lilensten, the creator of the Planeterrella. Here is the official information about these configurations.

- a) **Aurora ovals** (300V - 3000V, 10Pa - 100Pa, cathode: Needle, anode: Small sphere): The electrons are shot by the needle and, through the gradient drift and collisions described above, end up creating visible auroral ovals. Sometimes the ring current can be visible too. This reproduces the Sun shooting charged particles at the Earth.
- b) **Stellar wind and coronal holes** (cathode: Large sphere, anode: Needle): Because this sphere is larger, the emitted electrons are not confined as in the previous configuration. Instead, they propagate throughout the chamber, exciting and ionizing the rarefied gas. This results in the formation of a large plasma cloud, analogous to the expansion of a stellar corona. The magnetic poles repel the electrons and create visible holes in the plasma, called coronal "holes".
- c) **Stellar ring current** (300V - 3000V, 10Pa - 100Pa, cathode: Small sphere, anode: Needle): The electrons fired by the small sphere are immediately trapped in the ring current and create a bright Saturn-like ring with a radial color gradient. This configuration is extensively studied in [3]
- d) **Van Allen radiation belt** (cathode: Needle, anode: Large sphere): The electrons reaching the large sphere become trapped by its magnetic field and form a plasma envelope around it. The difference with the aurora ovals configuration (a) stems from the more complex magnet configuration within the large sphere, but also from the larger radius of the sphere. This configuration reproduces features analogous to the Van Allen radiation belts and the plasmasphere.
- e) **Magnetopause** (High intensity required, cathode: Large sphere, anode: Small sphere): Electrons are driven along a magnetic field line that connects opposite poles, north of the star to south of the planet, or south of the star to the north of the planet. This creates a

common zone between the 2 spheres where the electrons are concentrated enough so that the light emitted by gas excited through collisions becomes visible. This wall is visible on a simulation of the magnetic field (Figure 4.2).

- f) **Striations** (100+ PA, cathode: Large sphere, anode: Small sphere): This configuration is not an official one, it is described in Siebons [32]. It illustrates the spatial structure of a glow discharge. At sufficiently high pressure, electrons emitted by the cathode undergo frequent collisions with the gas and progressively lose energy as they propagate through the chamber. Close to the cathode, energetic electrons efficiently excite and ionize nitrogen, producing the characteristic blue emission dominated by the N_2^+ first negative system. Further from the cathode, the electron energy distribution changes and the emission becomes dominated by the N_2 first positive system, resulting in the characteristic red luminous regions, separated by a Faraday dark space. The spatial variation of the electron energy and excitation processes produces alternating regions of enhanced and reduced emission, known as striations [20].

2.2.3 LIMITATIONS

The Planeterrella is a physical analogy of space phenomena. There is no plasma flow, no proton source, and therefore it does not reproduce the magnetic reconnection associated with real auroras. The dimensions of the setup and the magnetic field do not preserve the real ratio of planetary magnetospheres. The pressure is limited to what is found at 70km of altitude, the low end of auroral altitude. The famous red and green glow from atomic oxygen is therefore impossible to reproduce. Even if the pressure gets lower, the size of the setup could lead to significant collisions with the glass and quench the reactions anyway.

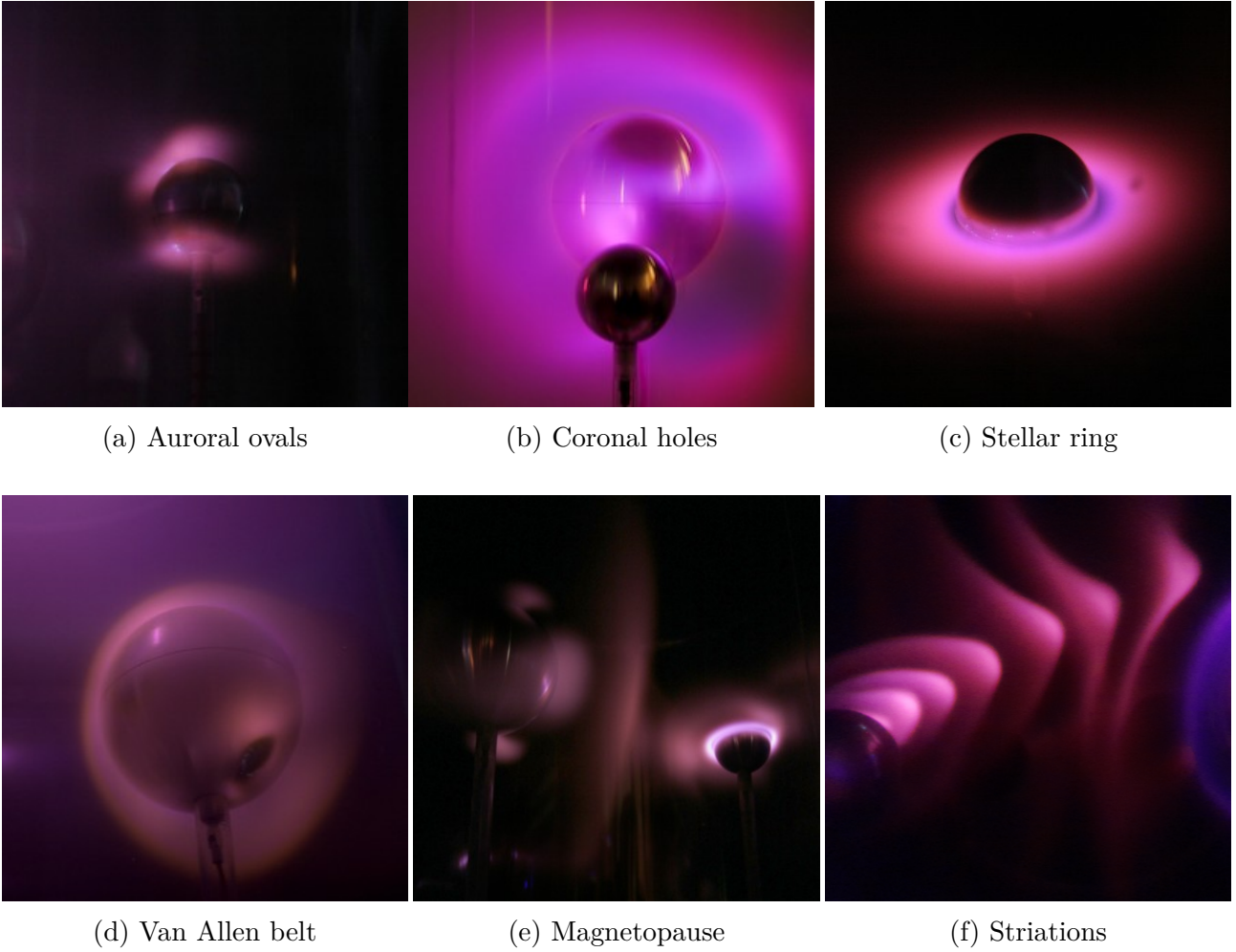


Figure 2.2: Sample of possible configurations for the Planeterrella. Pictures taken from the OSUG website [25] and from Siebons [32].

Chapter 3

Experimental setup

3.1 PLANETERRELLA

Our Planeterrella setup can be seen in Figure 3.1. It was built by Oliver Katz, cofounder of the AurorAlpes association [2], which regroups multiple Planeterrella users. It was based on the original blueprints of Jean Lilensten [19].

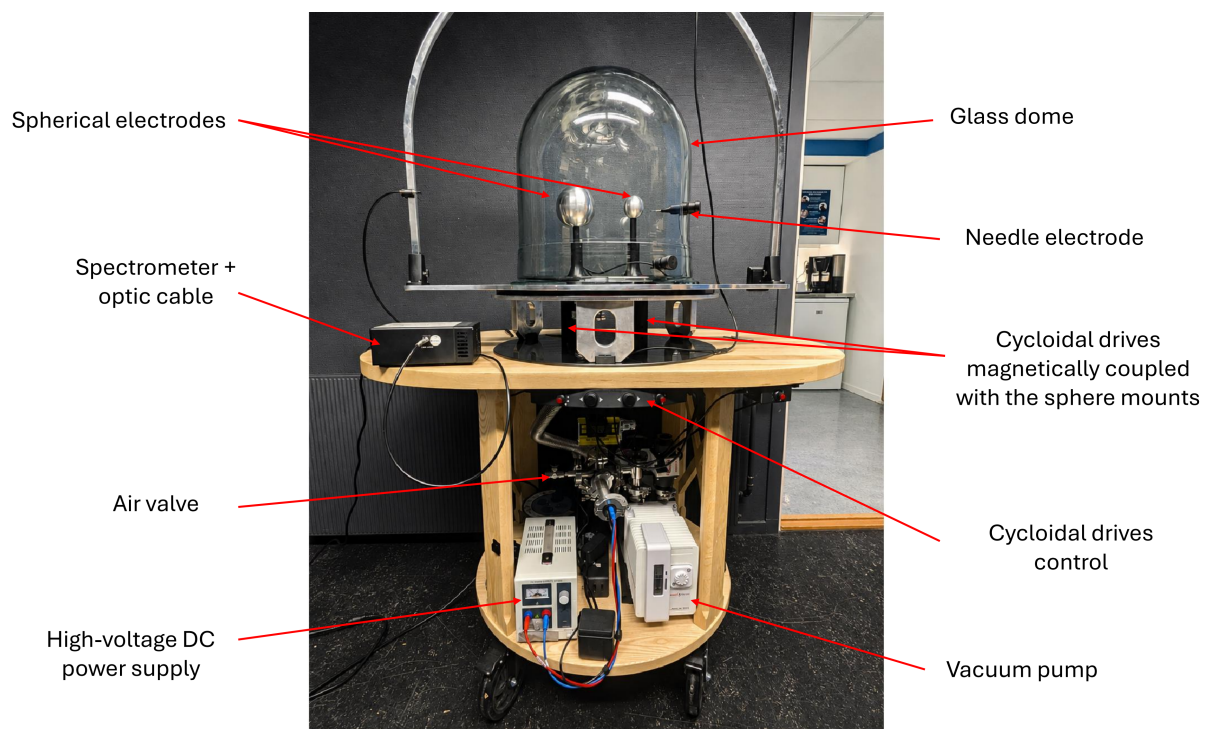


Figure 3.1: Planeterrella setup

The experiment is housed inside a borosilicate 3.3 glass vacuum chamber, allowing optical access to the plasma from every direction. The chamber is evacuated using a Pfeiffer Pascal 2015 SD, a two-stage, oil-sealed rotary vane vacuum pump [28], reaching ultimate pressures down to 0.05 Pa. The pressure is monitored by a vacuum gauge. The glass dome rests on a large aluminium baseplate, pressing a ring-shaped rubber gasket to ensure a good vacuum seal. The lowest pressure achievable is around 3 Pa, which is sufficient to observe a significant difference in plasma emission compared to the 10-100 Pa range. Contrary to intuition, leaving the vacuum pump running for an extended period of time does not improve the vacuum, but instead leads to higher pressures, likely due to the pump overheating and losing efficiency. This means running the pump for 30 minutes is largely sufficient to reach the lowest pressure settings. This also means the leaks are significant enough to compensate for the pumping speed after a few dozen minutes.

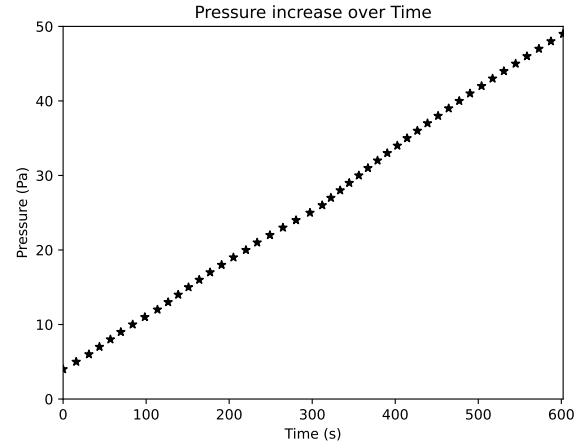


Figure 3.2: Pressure evolution due to leaks over time

The pressure evolution over time is shown in Figure 3.2, one can expect about a 1 Pa increase every 10 seconds. It is difficult to pinpoint the exact cause of the leaks, but it is likely due to the rubber gasket and the glass dome not being perfectly flat. Two main issues arise from this. First, the pressure is not stable over time except for the lowest pressure settings (equilibrium between leaks and pumping speed), this makes it difficult to perform long/multiple measurements at a specific pressure. Secondly, the leaks constantly introduce air into the chamber, which could potentially change the composition of the plasma over time. This means that, when introducing a new gas to the chamber (CO_2 , O_2 , ...), the emission spectrum quickly gets contaminated by the air, particularly at the lowest pressure settings, where the leaks are significant compared to the number of molecules in the chamber.

Inside the chamber, two out of three electrodes can be picked to create a plasma discharge. The two main electrodes, as of the first design of the Planeterrella, are two spherical electrodes of different sizes simulating the Sun and the Earth. The third electrode, a more recent addition, is a needle that can be used to create a more focused plasma discharge and also create a strong electric field around it. The two spherical electrodes are made of aluminium. The larger one has a diameter of 10 cm, and the smaller one has a diameter of 5 cm. They both contain a permanent magnet within to reproduce the magnetic field of the two celestial bodies. The surface of these spheres can vary a lot, from erosion by dust particles [14] to oxidation, which can change the plasma emission. The needle is 3 cm long and 3 mm in diameter, and is made of stainless steel. All three electrodes are magnetically coupled to the exterior of the chamber, allowing them to be moved around and rotated without breaking the vacuum. The spheres' magnetic mount is even connected to a cycloidal drive, allowing the spheres to be rotated at a constant speed.

To create a plasma discharge, a high voltage is applied between the two selected electrodes. The voltage is delivered by a 5 kV DC power supply from 3B SCIENTIFIC. Plugging an electrode to the cathode (-) will make it emit electrons (i.e. shooting particles like the sun), whereas plugging it to the anode (+) will make it attract electrons (i.e. receiving particles like the Earth). The power supply is limited to 5 kV, but the plasma discharge itself imposes a lower voltage depending on the pressure and electrode configuration. We tried measuring the intensity of the plasma discharge using a multimeter, but the current instabilities always led to inaccurate measurements and to the multimeter crashing. The current of such a plasma would typically be on the order of a few milliamperes, and the power supply caps at 2 mA. It could have been used as a diagnostic tool to measure the plasma density. A valuable upgrade for the Planeterra would be adding a Langmuir probe with a magnetic mount, just like the spherical electrodes, that would allow us to measure the plasma density and temperature wherever we want. This would only require passing 2 more cables

3.2 SPECTROMETER

The optical emission spectra from the Planeterra were measured using a BTC655 Exemplar Plus spectrometer by B&W Tek [4]. It is a "plug-and-play" device utilising a low-stray-light unfolded Czerny-Turner spectrograph. A Czerny-Turner spectrograph is an optical instrument composed of an entrance slit to create a small opening, a collimating mirror to make the rays parallel, a diffraction grating grid to split the light into different wavelengths, and finally a focusing mirror leading the light to a CCD sensor/camera (Fig 3.3).

The spectrometer is equipped with a thermoelectrically cooled back-thinned CCD detector to reduce dark current, making it able to measure weak plasma emissions. The current configuration, with a grating of 400 lines/mm and a slit width of $100\mu m$, covers 300nm to 1080nm with a resolution of about 4.5 nm. This range is spread over 2048 pixels, making it about 0.4nm/pixel. The detector also offers a 16-bit dynamic range, allowing both intense atomic lines and weaker molecular bands to be recorded within the same exposure.

To reduce ambient light contamination, the windows were covered with aluminium foil, as it is painfully long to wait for the night to fall in summer in the Arctic Circle.

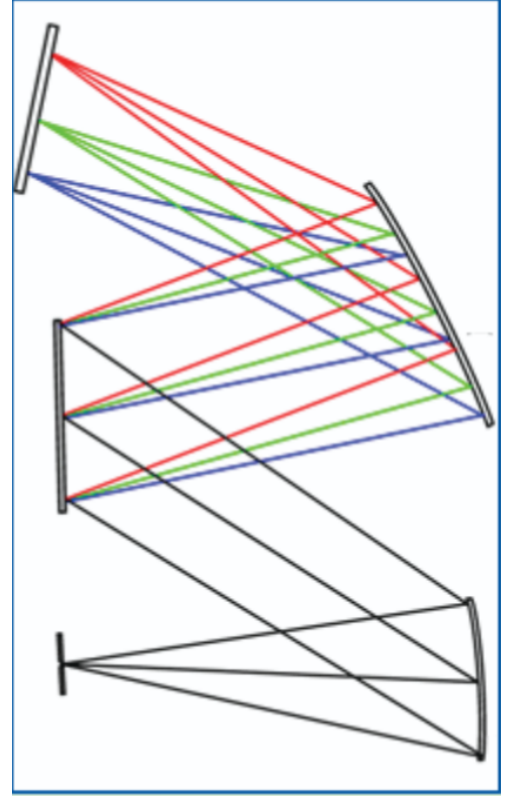


Figure 3.3: Czerny-Turner spectrograph diagram from [4]

3.2.1 WAVELENGTH CALIBRATION

We performed a wavelength calibration not only to ensure that the measured wavelength would reflect the actual associated phenomenon, but also to measure the effect of **secondary-order diffraction effects** [23]. If d is the slit-to-slit spacing of the grid, θ is the physical angle of the refracted light, and λ is the light's wavelength, then the diffraction grating satisfies the equation:

$$d \sin(\theta) = m\lambda, \quad m \in \mathbb{N}$$

This means for a single wavelength λ , multiple measurements may be encountered from different orders m :

$$\theta_m = \arcsin(m\lambda/d)$$

For example, a photon at 391.4 nm would also be diffracted in second order near 782.8 nm. Fortunately, this spectrometer is equipped with a Linear Variable Filter (LVF), which is placed on the CCD sensor to selectively block light arriving via higher diffraction orders, preventing a 782.8 nm second-order signal from contaminating the real 391.4 nm first-order signal at that pixel.

To check the efficiency of this filter and to proceed to the wavelength calibration, the spectrum of a mercury-argon lamp was measured and compared to reference wavelengths found on NIST [31]. The results are presented in Figure 3.4. All the resolved intensity spikes closely fit the NIST emission data within the 0.4 nm pixel resolution, meaning the spectrometer didn't require any tuning and successfully passed the wavelength calibration test. Between 700 and 1000 nm, the observed spectrum does not fit Hg second- or third-order emission. Instead, all these emission lines could be linked to Ar I, which is present in the tube. This means the integrated LVF successfully filters the secondary emissions to the point that they are no longer distinguishable. For the rest of this paper, we can assume that the secondary-order diffraction effect has a negligible effect on the measured spectrum.

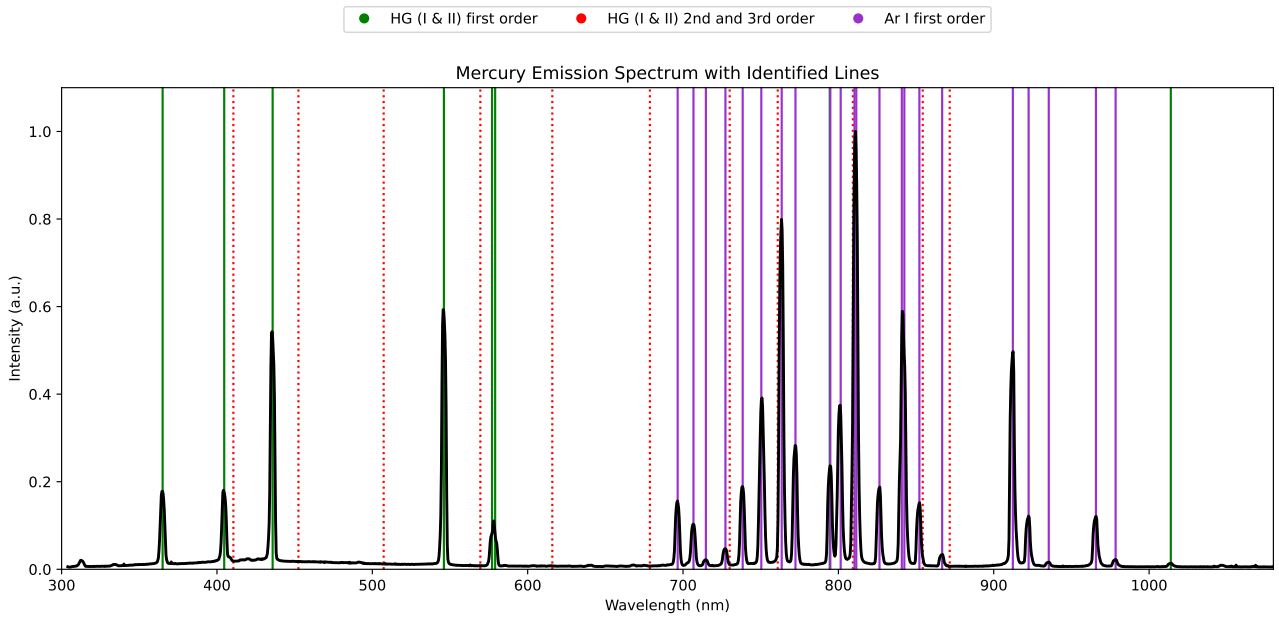


Figure 3.4: Wavelength calibration on a Hg-Ar lamp. The green and purple lines correspond respectively to the relevant Hg and Ar emission lines. The red dotted lines correspond to second- and third-order lines of HG (the second-order lines of Ar exceed the spectrometer range)

3.2.2 FLAT-FIELD CALIBRATION

The spectrometer flat-field response was calibrated using a tungsten-halogen lamp with a known spectral irradiance (Figure 3.5). The measured spectrum of the lamp was compared with its

certified reference spectrum [9] to determine the spectrometer's wavelength-dependent sensitivity. A correction function was then computed as the ratio of the reference to measured intensities and applied to all subsequent measurements. This allows for the compensation of the different elements of the spectrometer, from the CCD sensor sensitivity to the absorption in the optical cable used for measurements, and ensures the future emission records will more accurately represent the relative spectral intensity of the plasma.

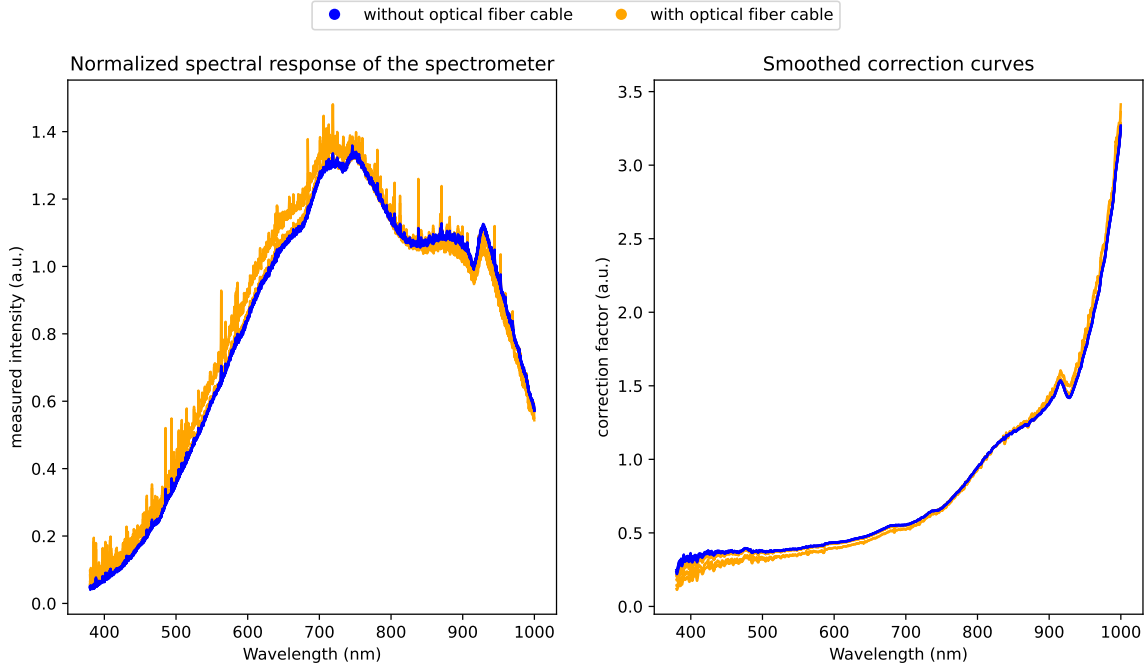


Figure 3.5: Flat field calibration. On the left, the normalized response of the spectrometer exhibits significant noise from cable measurements, but also the same global response. On the right, the correction curve using a certified reference, smoothed to remove the cable-introduced noise.

Measurements have been done with and without the optic cable, and with different exposure times. Once normalized, the spectrometer's response is independent of the exposure time. Even though the optical cable adds a significant amount of noise to the measured signal, its absorption coefficient seems uniform in the 300 nm to 1100 nm range, meaning its impact on the correction curve is minimal. Indeed, once smoothed to remove the noise introduced by the optical cable, the obtained correction curves look nearly identical.

However, the certified reference [9] only provides data for the range 380 nm to 1000 nm. This reduces the effective range of the spectrometer and limits the measurements of strong N2 emissions in the range 300 nm to 400 nm. Because the manufacturer explicitly claims, "The spectral distribution from the filament through the quartz envelope in the UV and Visible is essentially the same as a Black Body radiator at the lamp's apparent colour temperature of 2,990 K", we have decided to extend the calibration data using a blackbody radiation fit (Figure 3.6). The fit was done using the following spectral intensity formula, with A and T as

parameters.

$$I(\lambda) = A \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda kT)} - 1}, \quad W sr^{-1} m^{-2} nm^{-1}$$

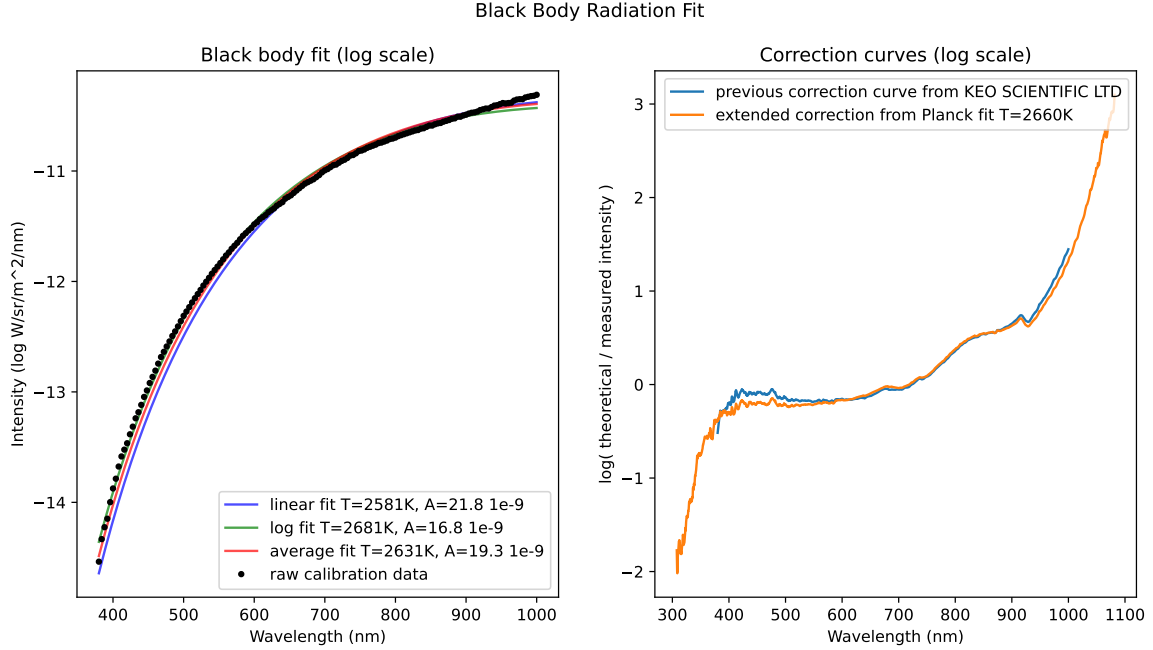


Figure 3.6: Results from black-body fit. On the left, different fits are compared to the raw calibration data. On the right, the extended correction curve is compared to the smaller one.

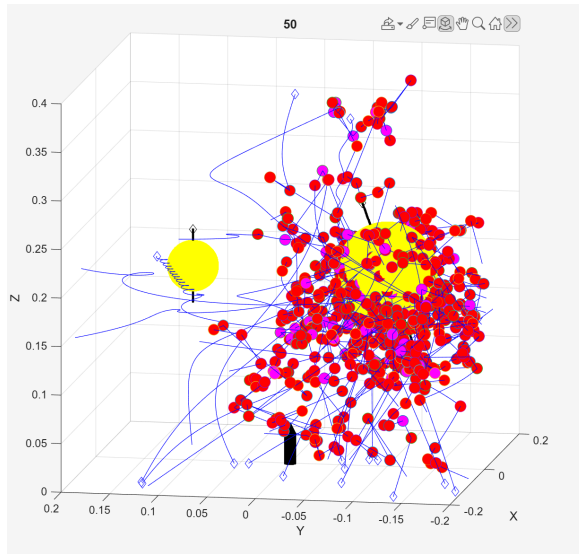
The black-body fit closely matches the official calibration data [9], but only for a temperature of around 2600K. Forcing a fit with $T > 2900K$ gave much worse results. This is likely due to the lamp being old. A synthetic spectrum with $T = 2660K$ was produced, covering the full range of the spectrometer, and used with the full-range measurement of the tungsten lamp to create a new extended correction curve. For the rest of the paper, this extended correction curve will be used to retrieve better emission spectra over the whole spectrometer's range.

This correction curve is adequate for the spectrometer specifically. However, it is technically possible to get an even more relevant correction curve. The glass dome containing the vacuum is made out of borosilicate 3.3, with significant absorption in the UV range ($\lambda < 350nm$). This absorption could potentially be corrected by modifying the correction curve. This has not been done in this paper.

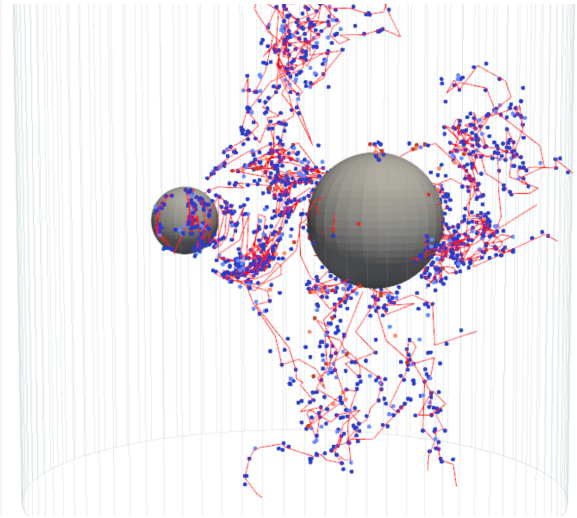
Chapter 4

Numerical modelling

The visible plasma emission of the Planeterrella is only a glimpse of the complex physical processes happening within. To better understand the physics of the Planeterrella, numerical models have been developed that simulate the behaviour of the electrons in the plasma. Mathieu Barthélémy, who had the opportunity to work on Planeterrellas at Université Grenoble Alpes, kindly provided us with a MATLAB model. In this chapter, we will present a slightly upgraded version of this model, written in Python, that allows for more flexibility, more accurate physics, and shorter computation times. The code is open-source and available on GitHub [5].



(a) Previous MATLAB simulation



(b) Python simulation

Figure 4.1: Simulation of the trajectory of 50 electrons in the planeterrella using the previous MATLAB code and the current Python code with t . In (a), the collisions with N_2 are magenta dots, and the ones with O_2 are red dots. In (b), the inelastic collisions are blue, whereas the elastic ones are red

4.1 MODEL OVERVIEW

The physics model of the original MATLAB code has been mostly conserved. The original simulation integrates individual electron trajectories under the spheres' magnetic fields, and models electron-neutral collisions (elastic and inelastic) with a Monte Carlo collision engine using real N₂ and O₂ cross-section data. This simulation then outputs a 3D rendering of the spheres (or needle if used) and the trajectory of the electrons. Viewing the trajectories of the electrons and the chaotic nature of their motion due to the collisions provides valuable insights into the physics of the Planeterrella.

However, the simulation was not very flexible, it was not possible to change the pressure settings, for example, and the 3D rendering was painfully laggy. This gave motivation to rewrite the code in Python, using a fast and efficient 3D rendering library called pyVista, and making the settings as flexible as possible. To make the new code easy to understand, it is structured in a more object-oriented way, with a clear separation between the different components of the simulation. The code is structured as follows:

```

Planeterrella-simulation/
├─ main.py .....Entry point — loads config, runs simulation, renders results
├─ config.toml All experiment parameters (geometry, gas, voltage, particle counts, etc.)
├─ src/
│   ├─ config.py .....Loads config.toml into an Experiment object
│   ├─ experiment.py .....Experiment container (geometry + gas + fields + settings)
│   ├─ geometry.py .....Planeterrella geometry: Dome, Sphere, Needle, Dipole
│   ├─ fields.py .....Magnetic and electric field models
│   ├─ particles.py .....Electron population state (position, velocity, alive mask)
│   ├─ Boris.py .....Boris pusher for particle integration
│   ├─ monteCarlo.py .....Electron emission sampling (cathode surface)
│   ├─ collisions.py .....Monte Carlo collision engine (elastic + inelastic)
│   ├─ gas.py .....Background gas (species, pressure, temperature)
│   ├─ diagnostics.py .....Trajectory & collision recording, HDF5 export
│   └─ renderer.py .....3D rendering (PyVista): geometry, fields, trajectories
└─ cross_sections/
    ├─ cross_section_elastic.py .....Elastic e-N2/O2 cross-sections
    ├─ cross_section_inelastic_N2.py .....N2 excitation/ionization channels
    └─ cross_section_inelastic_O2.py .....O2 excitation/ionization channels
  
```

4.2 FIELD MODELS

Even before the electrons are emitted from the cathode, the Planeterrella is already a complex system of electric and magnetic fields.

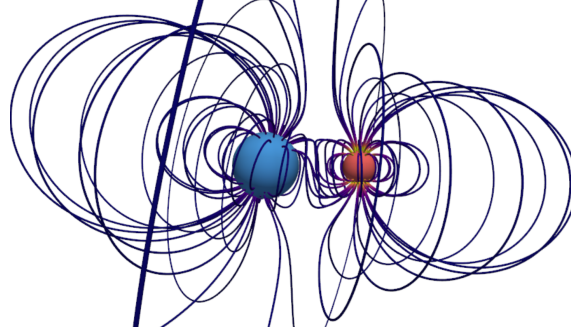


Figure 4.2: Magnetic field lines of the Planeterrella.

• MAGNETIC FIELD

The magnetic field is generated by the permanent magnets inside the spheres, the one holding the needle is neglected. These permanent magnets are modelled as magnetic dipoles, with a magnetic moment $\vec{m}$ of magnitude around 10 Am^2 , easily modifiable in the configuration TOML file. The magnetic field in the simulation is simply the superposition of the present dipole fields and is calculated using the following formula [13]:

$$\vec{B} = \sum_i \left(\frac{\mu_0}{4\pi} \left(\frac{3(\vec{m}_i \cdot \vec{r})\vec{r} - \vec{m}_i}{r^3} \right) \right)$$

Where $\vec{m}_i$ is the magnetic moment of the i -th dipole, $\vec{r}$ is the unit vector from the dipole to the point of interest (electron position), and r is the distance from the dipole to that point. The magnetic field is calculated at each time step for each electron in the simulation when needed. The magnetic field in the Planeterrella from the two spheres is displayed in Figure 4.2.

4.2.1 ELECTRIC FIELD

The original code didn't use any electric field; the voltage applied to the electrodes was only used to determine the initial velocity of the electrons. Then, their trajectories would be influenced only by the magnetic field and the collisions. This is because of the Debye screening effect, which states that the electric field of a charged particle is screened by the surrounding plasma. This means that the electrons in the plasma will rearrange themselves to cancel out any electric field, and the electrons will only feel the magnetic field after traveling a few Debye lengths from the cathode. The Debye length is typically much smaller than the size of the Planeterrella, and the electric field can therefore be neglected as a first approximation.

We still decided to add the possibility to include the electric field from the electrodes in the TOML settings to better simulate the emission of the electrons (electrodes are more likely to emit electrons where the E field is stronger, not uniformly across the surface) and to open the door to a potential PIC (Particle-In-Cell) simulation in the future. The electric field is

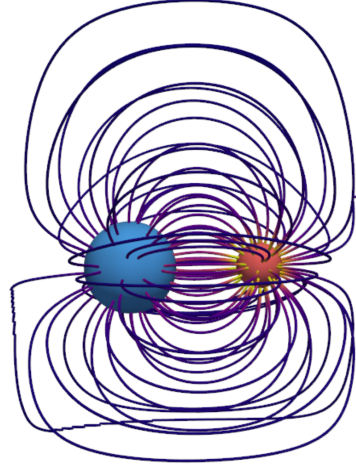


Figure 4.3: Electric field in an empty Planeterrella (no plasma) with the 2-sphere configuration.

calculated using a finite element method solver and is precomputed before the simulation starts. The electric field is then interpolated in the simulation when needed. A PIC simulation would allow the electrons to influence the electric field, and would therefore be able to simulate the Debye screening effect and maybe let us see complex phenomena such as the positive column glow observed in the Planeterrella at higher pressures. But this is beyond the scope of this paper and would be expensive both computationally and in terms of development time.

The electric field in the Planeterrella from the two spheres before the formation of the plasma is displayed in Figure 4.3. We can notice that the electric field bends around the glass dome. This is because we assumed the glass dome was an insulator, and therefore $\frac{du}{dn} = 0$; the directional derivative of the electric potential u normal to the glass surface is zero (Neumann boundary condition).

4.3 ELECTRON TRAJECTORY SOLVER

The original code used a Runge-Kutta (RK) method to solve the differential equation of motion for the electrons. This method is accurate and has the advantage of working for many differential equations, but it is not very efficient for long simulations with many electrons. We decided to use a Boris pusher algorithm instead [11], as it is much better suited for charged particles in an electric field. Whereas the RK method approximates the solution using polynomial increments, the Boris algorithm does a first half electric acceleration of the particles, then a magnetic rotation (with no associated work), and a final half electric acceleration. This is more efficient for long simulations because this ensures no energy is provided by the B field, whereas the RK errors accumulate over time (Figure 4.4).

Changing this method implied changing the way the simulation time step dt was computed.

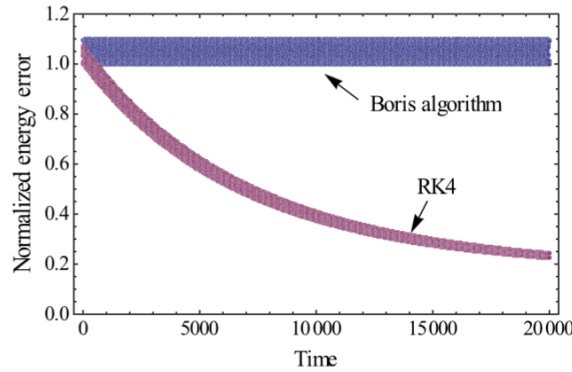


Figure 4.4: Difference between Boris and Runge-Kutta in energy error from [30]. This error is not bounded when using Runge-Kutta.

The original code used a Runge-Kutta method with an adaptive simulation time step, which was based on the local error estimate of the integration. This method is not compatible with the Boris pusher algorithm. We decided to set the time step as a fraction of the cyclotron period, which is the time it takes for an electron to complete one orbit around a magnetic field line. This ensures that the time step is small enough to accurately capture the motion of the electrons in the magnetic field, while still being large enough to allow for efficient simulations. The simulation time step dt is shared across all electrons to keep them all in sync. Technically, because the electrons don't interact with each other, each could have its own time step. However, if the code is upgraded to take into account the influence of the electrons on the electric field, a common time step would be necessary.

Because there is no electric field in the simulation, nothing is actively repelling the electrons from the cathode. After a few collisions, some unlucky electrons will therefore be sent back into the cathode. But an electron getting too close to the magnetic dipole inside the cathode will experience a drastically shorter cyclotron frequency, and will make the global simulation time step drop to near zero. The code handles this by killing the electrons which leave the domain, that is, outside the dome and inside the spheres. This makes the simulation faster and more stable, as the electrons which are absorbed by the anode at the end of their journey, get too far away, or are reflected into the cathode are no longer simulated.

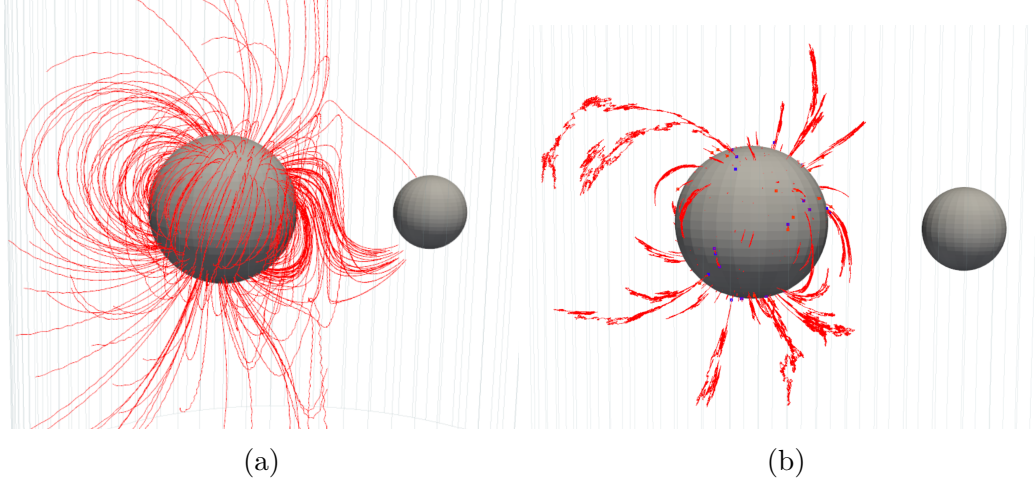


Figure 4.5: Trajectory of 500 electrons in the Planeterrella simulation emitted from the larger sphere. (a) Without collisions, the electrons follow smooth helical paths along the magnetic field lines. (b) With collisions, the trajectories become chaotic and scattered due to interactions with gas particles. Many electrons are absorbed back into the sphere due to early collisions.

4.4 COLLISION ENGINE

At every time step, the simulation checks every electron for a potential collision with a gas particle. Because the cross-section of the collisions depends on the energy of the electrons, they need to be calculated at every time step for every electron. This process is computationally expensive, so the functions were optimized using Numba [24] for the inelastic cross-sections and using a precomputed interpolation table for the elastic cross-sections. Once this data is computed, the simulation uses a Monte Carlo method to determine if a collision occurs and, if so, what type of collision it is. The Monte Carlo method uses random numbers to simulate the probability of a collision occurring based on the cross-section data. If a collision occurs, the simulation updates the electron's velocity and position accordingly.

Following the original code, here is the list of the collisions that are modeled in the simulation:

- Elastic collisions with N_2 and O_2
- Inelastic collisions with N_2
 - Excitation: $N_2 + e^- \rightarrow N_2^* + e^-$
 - * $A^3\Sigma_u^+ \rightarrow X^1\Sigma_g^+$ (Vegard-Kaplan system)
 - * $B^3\Pi_g \rightarrow X^1\Sigma_g^+$ (Wilkinson-Ogawa-Tanaka system)
 - * $C^3\Pi_u \rightarrow X^1\Sigma_g^+$ (Hopfield-Tanaka system)
 - * $C^3\Pi_u \rightarrow B^3\Pi_g$ (N_2 Second Positive System, 2PG)

- * $B^3\Pi_g \longrightarrow A^3\Sigma_u^+$ (N_2 First Positive System, 1PG)
- * $a^1\Pi_g \longrightarrow X^1\Sigma_g^+$ (Lyman–Birge–Hopfield system, LBH)
- Ionization : $N_2 + e^- \rightarrow N_2^+ + 2e^-$
 - * $X^2\Sigma_g^+$ (Production of N_2^+ in the ground state)
 - * $A^2\Pi_u \longrightarrow X^2\Sigma_g^+$ (Meinel system of N_2^+)
 - * $B^2\Sigma_u^+ \longrightarrow X^2\Sigma_g^+$ (N_2^+ First Negative System, 1NG)
- Inelastic collisions with O_2
 - Excitation: $O_2 + e^- \longrightarrow O_2^* + e^-$
 - * $B^3\Sigma_g^- \longrightarrow X^3\Sigma_g^-$ (Schumann–Runge system; labeled $C^3\Sigma_u^-$ in older literature)
 - *
 - * $a^1\Delta_g \longrightarrow X^3\Sigma_g^-$ (Infrared Atmospheric system)
 - * $b^1\Sigma_g^+ \longrightarrow X^3\Sigma_g^-$ (Atmospheric system)
 - * $A^3\Sigma_u^+ / A'^3\Delta_u / c^1\Sigma_u^- \longrightarrow X^3\Sigma_g^-$ (Herzberg I, II, and III systems; unresolved triplet)
 - Ionization : $O_2 + e^- \rightarrow O_2^+ + 2e^-$
 - * Production of O_2^+ in the ground state ($X^2\Pi_g$)
 - * Production of O_2^+ in the $b^4\Sigma_g^-$ state ($b^4\Sigma_g^- \longrightarrow a^4\Pi_u$: O_2^+ First Negative System)

It is important to note that even though the simulation considers ionization collisions, no new electrons nor positive ions are created in the simulation. The simulation only shows what collisions occur and where they occur, but does not change the state of the neutral species.

Once all of these cross-sections are computed, the probability of collision is

$$P = 1.0 - e^{-\nu_{tot}dt}$$

where ν_{tot} is the total collision frequency, which is calculated by summing $\nu = n\sigma v$, where n is the number density of a gas species, σ is the cross-section of the collision, and v is the velocity of the electron. The simulation uses a random number generator to determine if a collision occurs based on this probability. If a collision occurs, the simulation updates the electron's velocity. If it's an elastic collision, the electron's velocity changes direction in a forward-peaked scattering manner. If it's an inelastic collision, the electron's velocity is reduced by the energy lost in the collision, and the electron gets a new random direction.

Attempts have been made to include the colour emitted by the gas particles after inelastic collisions. This, however, would require radiative rate A or lifetime τ data and the quenching

rate coefficients k_q for each excited state, as the fraction of excited states that actually produce a photon is given by the effective radiative quantum yield $\eta = A/(A + k_q[M])$ discussed in the Theory chapter. Finding this data could provide a valuable visual update to the simulation.

4.5 SIMULATION RESULTS

4.5.1 PLASMA ASYMMETRIES

Running the planeterrella at 20 Pa, setting the larger sphere as the cathode and the smaller one as the anode, one can notice that the plasma forming around the smaller sphere is not symmetrical. A bulge of plasma seems to be forming on the bottom side of this sphere, where the auroral oval usually sits. A picture of this phenomenon is shown in Figure 4.6(a). Simulating 500 electrons with similar parameters allows for a better understanding of the electrons' trajectory. Starting from a uniform distribution around the cathode, the simulation shows that, among all the paths leading to the anode, the ones reaching it from the bottom side are more numerous than the ones from the top and therefore more densely populated and visible.

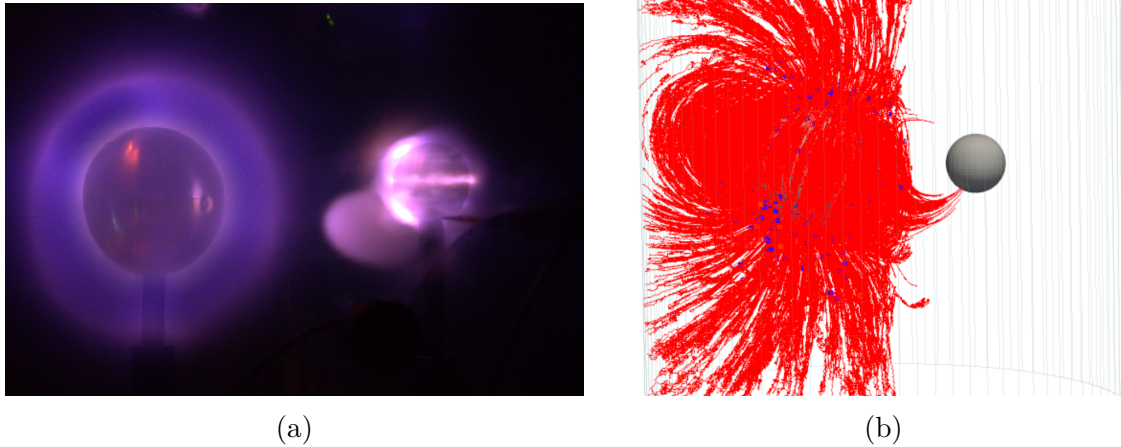
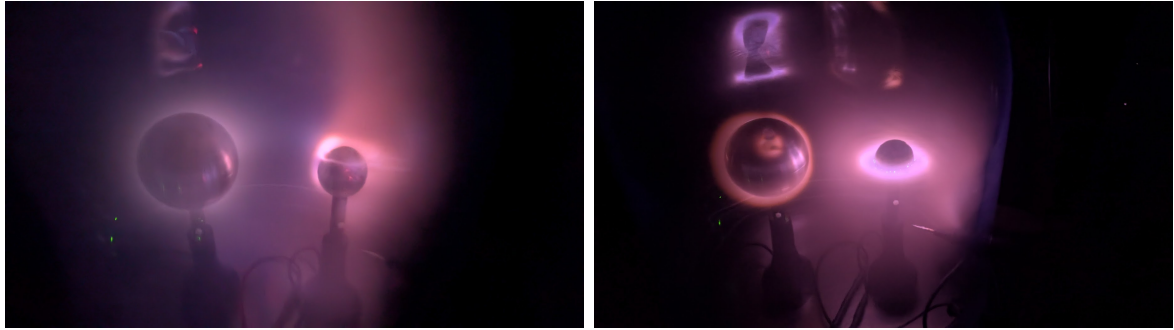


Figure 4.6: Simulation of an observed asymmetry in the Planeterrella. (a) Picture of the phenomenon in the Planeterrella, showing a bulge on the bottom auroral oval of the smaller sphere. (b) Simulation of the same configuration.

4.5.2 STELLAR RING

A trajectory-wise particularly interesting configuration of the Planeterrella is the stellar ring current configuration [25]. More information about this configuration is explained in the theory section 2.2.

At the lowest pressure setting of 4 Pa, with the maximum voltage applied, the difference between setting the bigger sphere or the smaller one as the cathode is striking. This difference is visible in Figure 4.7; the only difference in the experiment settings between these two configurations is the polarity.



(a) Traditional configuration (Bigger sphere as cathode) (b) Stellar ring configuration (polarities are inverted)

Figure 4.7: Visual difference from a simple polarity switch.

However, because of the absence of the electric field, nothing repels the electrons from the spheres. This is a significant difference, and this also means we won't be able to simulate the Debye sphere, the empty space enveloping the sphere. Despite this, the results still showed convincing trajectories.

First, the traditional configuration was simulated with 2k electrons, 100k time steps, and a pressure of a few pascals. Many electrons were used in the simulation to counteract the absorption effect due to the lack of a repelling electric field. The results of the simulation are presented in Figure 4.8. The electrons experienced a simulation time of $1.1\mu s$ on average before being absorbed and travelled 29cm on average. They experienced 17k inelastic collisions and 2.5k elastic collisions, leading to a mean free path of 3.4cm.

Then, the simulation was run with the same parameters, but with inverted polarities. The results of this simulation can be found in Figure 4.9. The electrons experienced a simulation time of $2.2\mu s$ on average before being absorbed and travelled 43cm on average. They experienced 27k inelastic collisions and 2.7k elastic collisions, leading to a mean free path of 3.3cm.

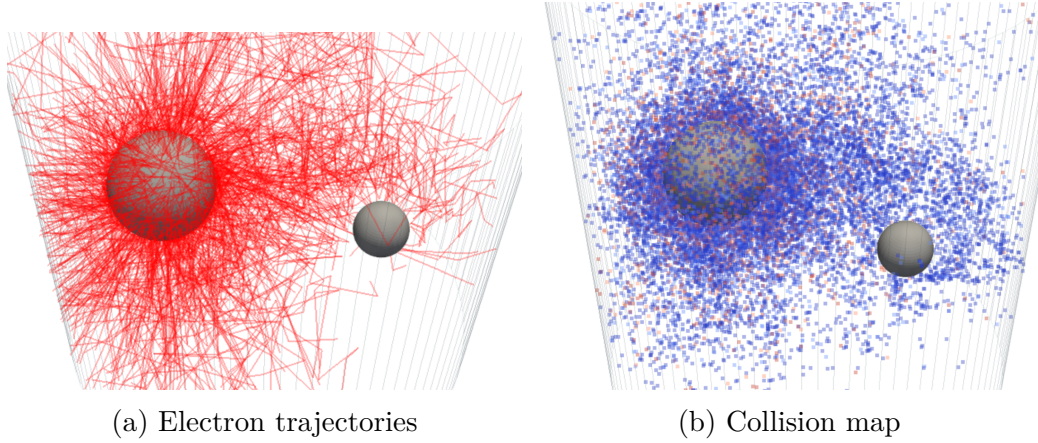


Figure 4.8: Result of the simulation in the traditional configuration, with the large sphere as the cathode and the small one as the anode.

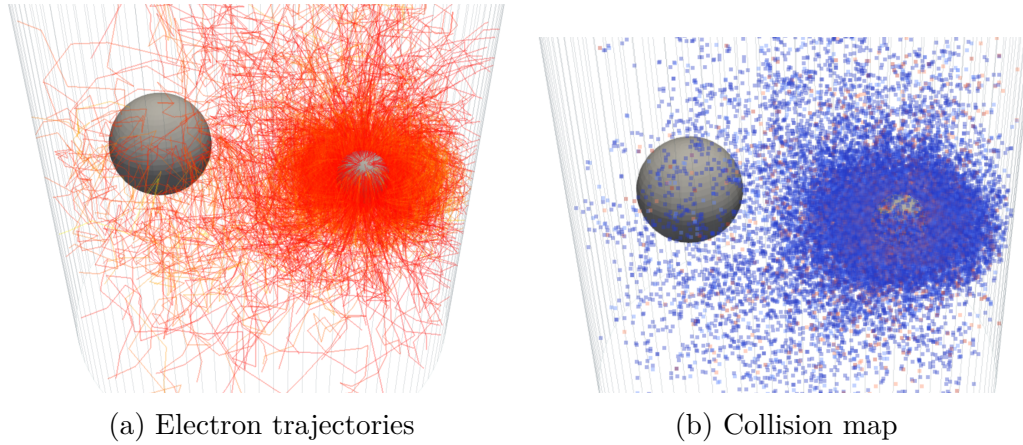


Figure 4.9: Result of the simulation in the stellar ring configuration, with the small sphere as the cathode and the large one as the anode.

The electron trajectories were plotted with a colour gradient, turning from red to yellow following their time evolution. We can notice that in the traditional configuration, the electrons radiate uniformly from the large sphere, quickly escape the magnetic field, and are quickly absorbed. In the stellar ring configuration, the electrons stay trapped much longer in the magnetic field. We can notice that the trajectory lines turn yellow while still orbiting the smaller sphere, meaning the electrons stay much longer "in orbit". This is backed up by the fact that the average lifetime of the electrons before absorption is doubled in this configuration compared to the traditional one. The collisions reveal the same results. In the traditional configuration, the collisions form a somewhat uniform cloud around the large sphere before heading to the anode. In the stellar ring configuration, the collisions form a denser doughnut-shaped cloud where the stellar ring is observed in the physical setup.

Chapter 5

Experimental results

5.1 SPECTRAL MEASUREMENTS OF THE PLANETERRELLA CONFIGURATIONS

All the configurations presented in Section 2.2.2 have been reproduced successfully with the UNIS' Planeterrella and studied. To obtain the high-intensity "Magnetopause" configuration, we realised that adding ethanol to the rarefied air considerably enhanced the plasma emissions. We propose that, since the ionization energy of ethanol is lower than that of N₂, more electrons are created by collisions with the suprathermal electrons, which induce a higher current in the plasma. This section will provide the settings used to obtain different configurations with the UNIS Planeterrella, as well as spectral measurements of the phenomena in different conditions.

Because this report is limited in length, only the configurations "Aurora ovals" and "Coronal expansion" will be presented here. They have been chosen because they represent the "canonical setup" (Sun shooting particles creating Auroras on Earth). Results of the other configurations will be handed to UNIS in a different version of this report.

5.1.1 AURORA OVAL

In short: Set the needle as the cathode and the small sphere as the anode. Set the pressure to lowest and scan the voltage from maximum to minimum to find the best configuration and avoid the current ring.

Funnily enough, obtaining the aurora oval can be quite a difficult process. The plasma emissions around the small sphere appear to have multiple stable forms, presented in Figure 5.1. The plasma can quickly oscillate between these two forms, staying in one configuration for only a few seconds before instantly switching to the other. This whole process is really sensitive to pressure, voltage, the position of the electrodes, and the surface condition of the small sphere.

Lowering the voltage often leads to the plasma stabilizing in the aurora ovals, at the cost of luminosity. Lowering the pressure also helps the stability of this configuration. Placing the needle directly above the small sphere also helps.

If the sphere's surface is too damaged, it will be very difficult to obtain the aurora ovals, as the current ring will dominate. A polishing would then be required to observe this configuration again.



(a) Aurora oval dominating

(b) Ring current dominating

Figure 5.1: Pictures of the two stable forms the plasma oscillates between.

An example spectrum of the Planeterrella in this configuration is already presented on the OSUG website [25]. However, this spectrum doesn't seem to have benefited of a correction curve, and the intensity of the emissions collapses past 800nm. We aimed to measure and label a wider spectrum of the "Auroral oval" configuration in the range 300nm to 1100nm. Our results, for pressure $P = 5$ Pa and using maximum voltage settings of the power supply, are presented in Figure 5.2. The data for the molecular nitrogen N_2 emission spectrum, including N_2 first positive (N2FP) N_2 second positive (N2SP) N_2^+ first negative N2PFN and N_2^+ Meinel bands, have been collected from David Bernard's PhD [6], who measured precisely the emissions of the Planeterrella in the range 350-700 nm, and from Mangina [21] presenting a visible-optical-near-IR wavelength range spectrum of molecular nitrogen. The atomic nitrogen lines and oxygen lines are based on the NIST data (although incomplete) of these atoms [31], on Bernard's PhD and Mangina [21] for more precision in the visible range, and on Kozubal[18] for infrared data. The data for the molecular oxygen O_2 , mainly O_2^+ first negative, originate from Vallance Jones [16], Mathieu Barthelemy [22] and C A Terrell [8].

The spectra of the molecular species, most importantly N_2 , N_2^+ , and O_2^+ , are very broad and often overlap, making it difficult to pinpoint which species are causing the observed emission lines. To help distinguish between the species, spectral measurements have been made in the Planeterrella using pure N_2 and pure O_2 . This helped distinguish the contribution of O_2 and O_2^+ independently from N_2 and N_2^+ . To distinguish between the neutral X_2 and ionized X_2^+ versions of these molecules, the spectra of the anode and cathode have been compared, as the cathode concentrates significantly more of the ionized molecules due to the Debye screening.

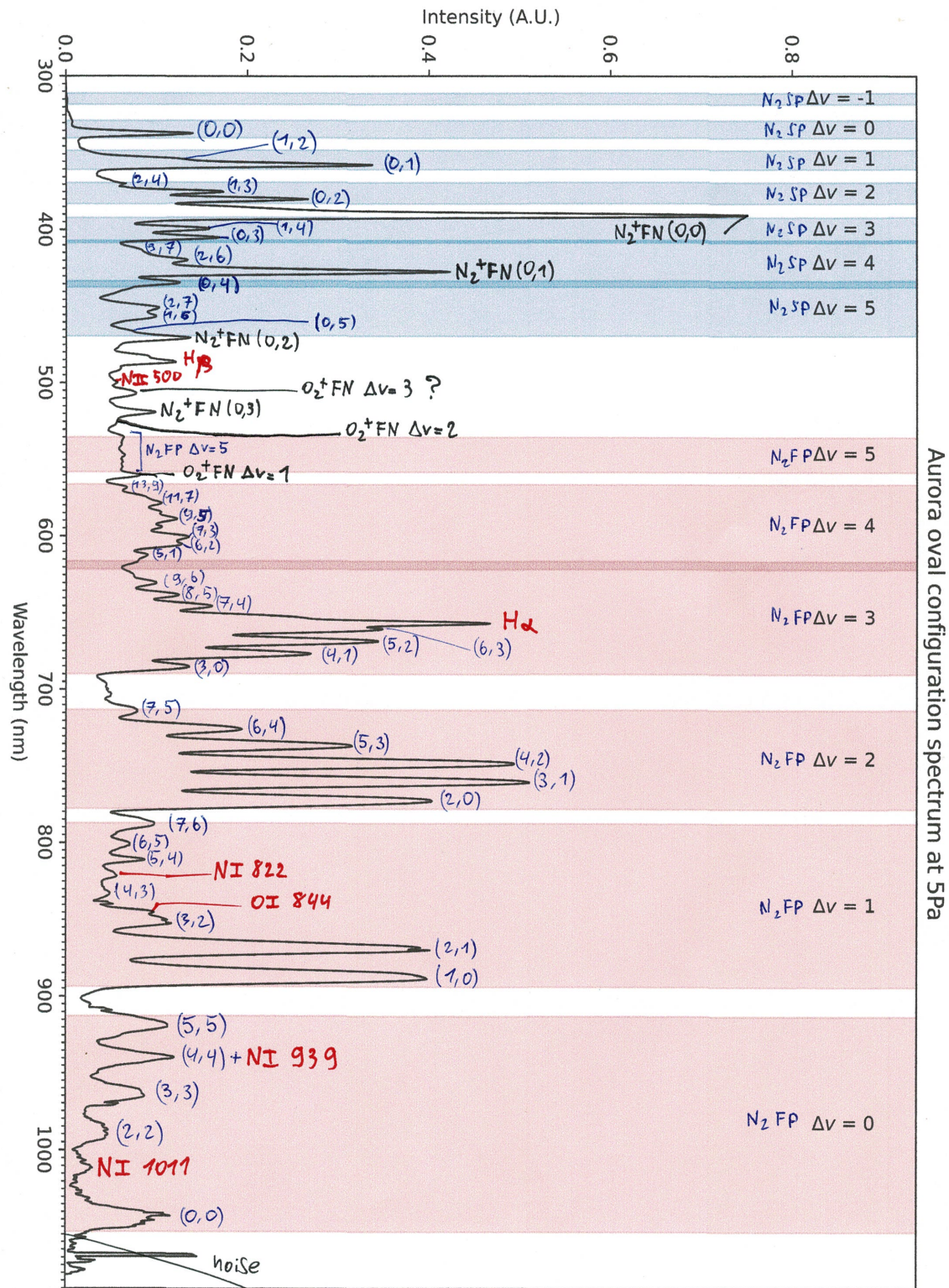
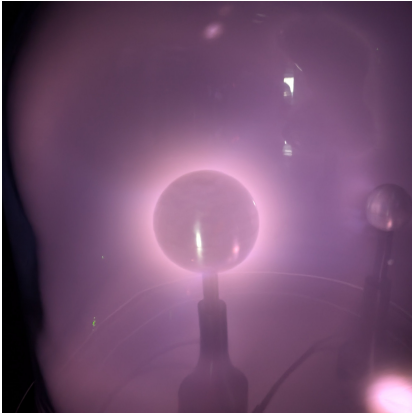


Figure 5.2: Annotated spectrum of the aurora oval configuration of the Planeterra at pressure $P = 5$ Pa

5.1.2 CORONAL EXPANSION AND CORONAL HOLES

In short : Set the large sphere as the cathode and the needle as the anode. Set the pressure to ~ 15 Pa and the voltage to maximum.

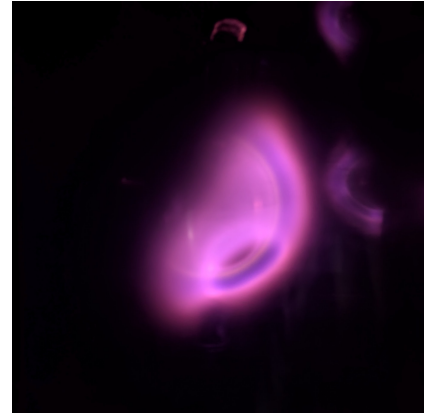
This configuration is really easy to obtain and very stable. It is better not to lower the pressure to the absolute minimum limits of the Planeterra, because then the coronal expansion becomes so large it's not visible anymore; everything blends into a homogeneous cloud filling the chamber (figure 5.3). We would recommend setting the pressure between 10 and 20 Pa. The choice of the anode (needle, small sphere) and its position have a minimal impact on this configuration. The pressure and voltage have similar inverted roles. The corona expands with a decrease in pressure or an increase in voltage.



(a) 5 Pa, too large



(b) 15 Pa



(c) 30 Pa, not fully formed

Figure 5.3: Pictures of the coronal expansion in different settings.

With the same sources as the previous subsection, the annotated spectrum of this configuration in the range 300nm to 1100nm for pressure $P = 5$ Pa and using maximum voltage settings of the power supply is presented in Figure 5.4.

5.1.3 STELLAR RING

In short : Set the small sphere as the cathode and the needle as the anode. Set the pressure to ~ 10 Pa and the voltage to maximum.

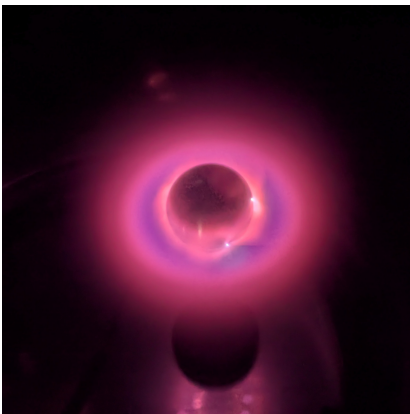
Warning : This configuration causes erosion of the small sphere's surface.

Probably the easiest configuration to obtain and the most striking one. The configuration is very resilient, and will be visible at any pressure and voltage setting. It is not sensitive to the relative position of the spheres. It is also the brightest configuration, so the easiest to observe when the Planeterrella can't be used in a dark room.

For the best results, the voltage should be set to the maximum to increase its brightness. The pressure should be set to a few pascals. Low enough to allow the electrons to be quenched, but not too low to avoid the plasma being too faint. The range 10-20 Pa seems to give the best results.

The cathode should be set to the small sphere, and the anode to either the large sphere or the needle. Setting the large sphere as the anode will induce the Van Allen radiation belt configuration at the same time, whereas choosing the needle will only display the stellar ring.

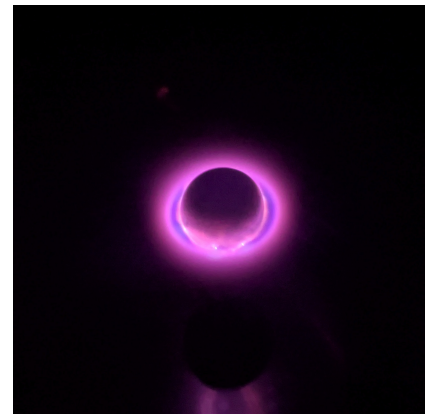
This configuration has a significant drawback, though. It brings the dust inside the Planeterrella close to the cathode and produces significant sparking in the equatorial region. This results in numerous impacts on the sphere's surface, thus altering the configuration. The rougher the surface is on the equatorial region, the more stable the current ring will be. This ends up being very detrimental to the Aurora oval configuration, which constantly alternates between the aurora oval and the ring current. Running the Stellar Ring configuration for a long time will therefore make it impossible to obtain the Aurora oval configuration. This is not irreversible, though, the damage is very superficial. Opening the Planeterrella and sanding down the surface with water and sandpaper will make the sphere good as new.



(a) Ring's color gradient



(b) Horizontal view



(c) Higher pressure settings

Figure 5.5: Stellar ring configuration.

5.1.4 VAN ALLEN BELT

In short: Set the needle as the cathode and the large sphere as the anode. Set the pressure near its lowest value (5–10 Pa), and gradually decrease the voltage from its maximum value until the Van Allen belt is fully visible.

This configuration requires a fairly precise adjustment of the pressure and voltage to obtain the best results. If the pressure is too high, the Van Allen belt will not cover the whole sphere. When the pressure is lowered, the electrons eventually "blast away" the Van Allen belt, leaving the large sphere bare. The objective is therefore to lower the pressure to around 5–10 Pa and then fine-tune the voltage to obtain the brightest and most complete Van Allen belt possible. The voltage needs to be relatively low. Beware that the Planetterella acts like a capacitor, and the voltage takes a few seconds to stabilize after a change. The extremes of the configurations are presented in Figure 5.6.

It is recommended to set the needle as the cathode in order to preserve the small sphere from damage caused by the current ring configuration. The direction of the needle also has some impact on the shape of the Van Allen belt, feel free to experiment with its orientation.



(a) Pressure set too high

(b) Low pressure and appropriate voltage

(c) Voltage set too high

Figure 5.6: Extremes of the Van Allen belt configuration.

5.1.5 MAGNETOPAUSE

In short: Set the small sphere as the cathode and the large sphere as the anode. Set the pressure to ~ 10 Pa and the voltage to maximum. Add a **small amount of ethanol** to the air inside the Planetterella.

This configuration is one of the "High intensity" configurations. It requires a high current that our power supply is not able to provide. It is theoretically out of reach for our Planeterrella. However, we discovered a way to cheat and obtain a similar configuration by adding a small amount of ethanol to the air inside the Planeterrella. This ethanol doping process is explained in Section 6.1. To get the best results, the voltage should obviously be set to the maximum, and the pressure should be set at $\tilde{10}$ Pa.

Using this method, we were able to obtain a very bright and stable magnetopause configuration Figure 5.7.

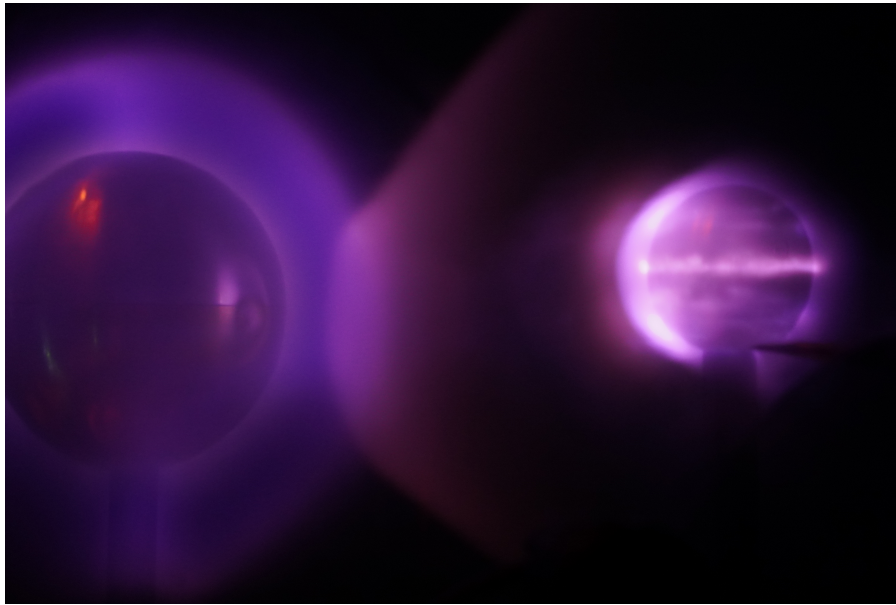


Figure 5.7: Magnetopause configuration with ethanol doping

On this picture, the large sphere was set as the cathode, and the small one as the anode. Swapping the polarities might give an even better result, but this haven't been done yet.

Our knowledge about ethanol doping is still limited. It is possible that if too much ethanol is added (just after a generous cleanse for example), chaotic and unstable configurations will appear (see Figure 6.1), but this is also highly dependent on the pressure.

5.1.6 STRIATIONS

In short: Set the large sphere as the cathode and the small sphere as the anode. Set the pressure to > 100 Pa and the voltage to maximum. When a red glow appears on top of the cathode emission, slowly lower the voltage until striations appear.

This configuration encapsulate a lot of different phenomena that are not reported on the OSUG website. At high pressures settings, > 100 Pa, a red glow appears on top of the cathode emission,

a few centimeters away. At such pressures, the plasma is not able to boot up on its own, but is able to sustain itself. To reach this configuration, one should first set the pressure low enough to allow the plasma to start, and then increase the pressure until the red glow appears. This glow is visible on the left picture (a) of Figure ???. The large sphere on the left was set as the cathode, and the small sphere on the right as the anode. The voltage was set to maximum. Once the red glow is visible, one can stop raising the pressure and start slowly lowering the voltage. The red glow will start to constrict, and striations will appear. The striations are visible on the middle picture (b). The plasma appears to discharge in midair, and the cone shaped striation will move around on the cathode's surface. Lowering the voltage even more will make the striation instantly move between the two electrodes, forming a stratified positive column, as seen on the right picture (c).

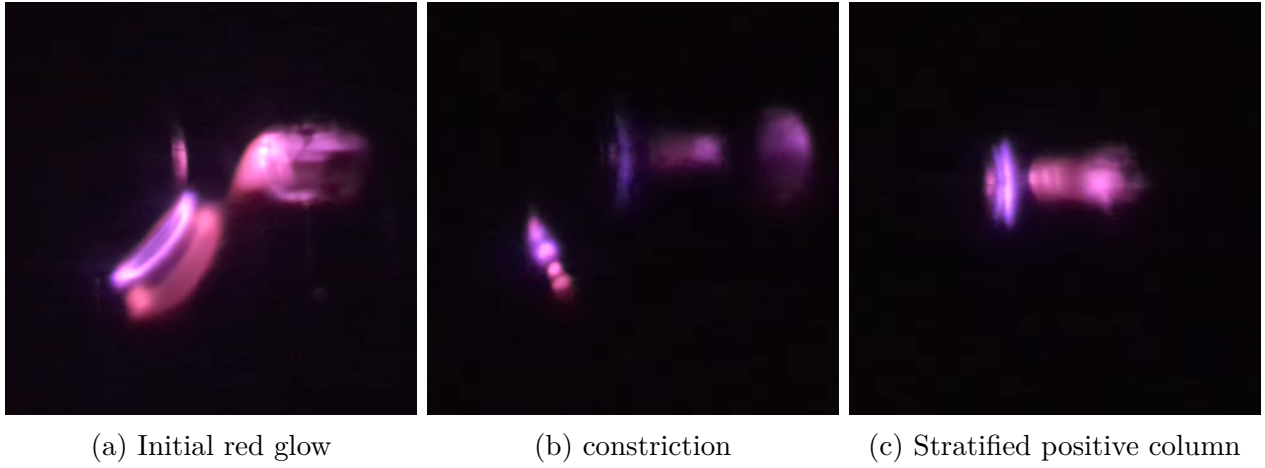


Figure 5.8: Evolution of the striations when lowering voltage at 100Pa.

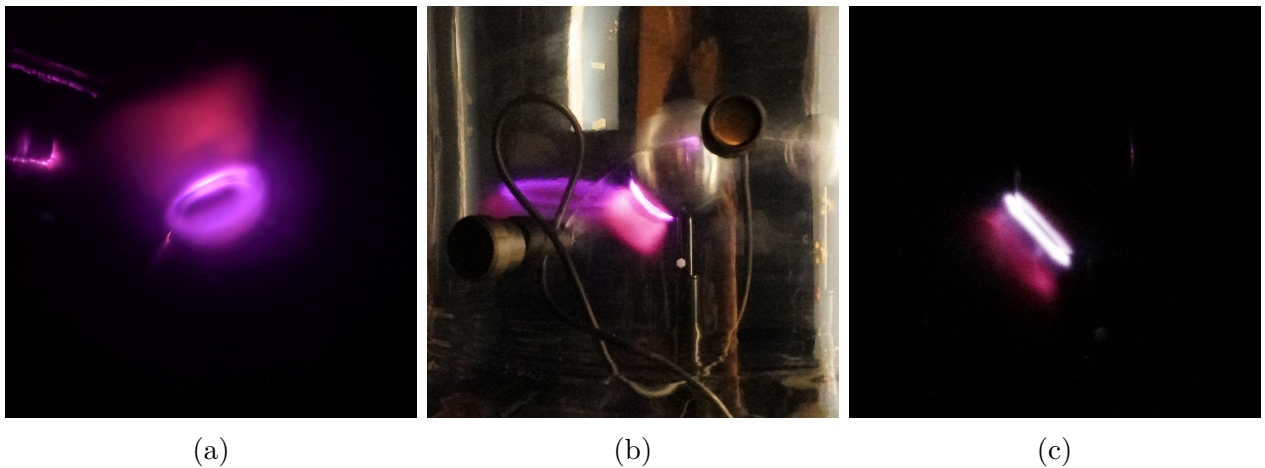


Figure 5.9: Example of red glow. The red glow appears as a large red cloud 1-2 cm away from the cathode emission. It can form a thin ring or a thick chunk depending on the pressure settings.

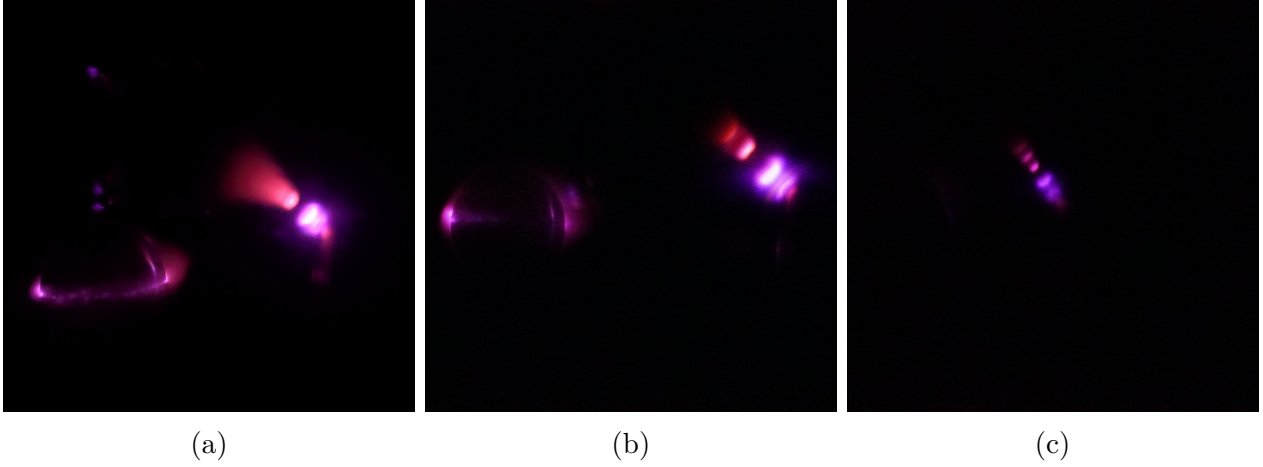


Figure 5.10: Example of constricted red glow. As the voltage is lowered, the red glow constricts into a cone and forms a positive column with increasing striations. This cone seems to be oriented in random directions, it does not always point towards the anode or follow the magnetic field lines.

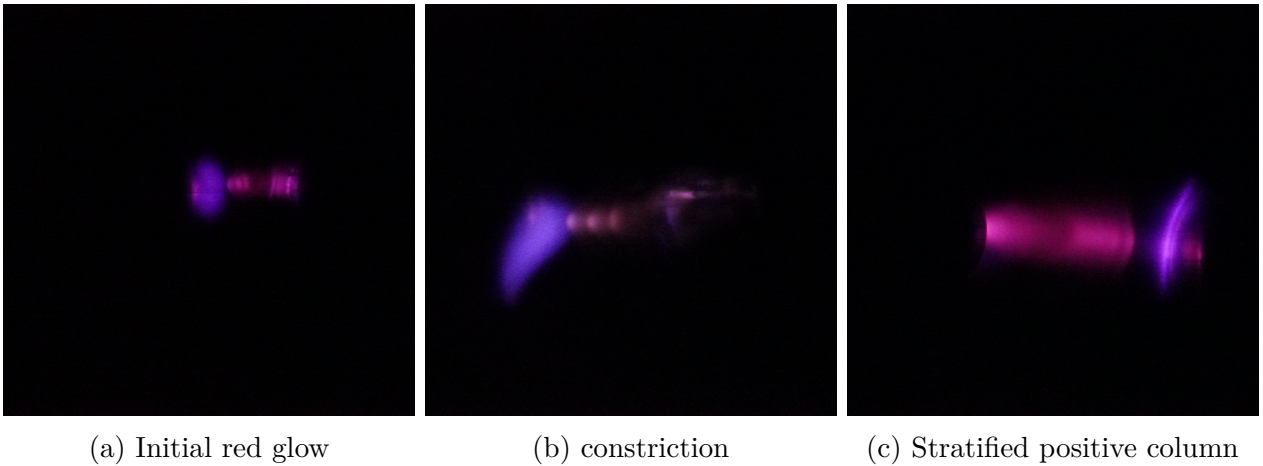


Figure 5.11: Before switching off, the striations suddenly move between the two electrodes. Many striations are observed in a short time. On the pictures, the purple glow indicates the position of the cathode (on the left), the anode is located at the source of the red emissions on the other side.

5.1.7 UNOBSERVED CONFIGURATIONS

The OSUG website [25] presents other configurations that we were not able to reproduce. The "Uranus" configuration, for example, should show the formation of auroras of the bottom of the small sphere but not on the top when this sphere is being shot by electrons from the needle

aimed at its top pole. We were not able to reproduce this configuration, the auroras always happened on both poles. After discussing with other Planeterrella experimenters, we realized none of them were able to reproduce this configuration either. So if you manage to get this configuration to work, please take some pictures. Better results could maybe be obtained using ethanol doping.

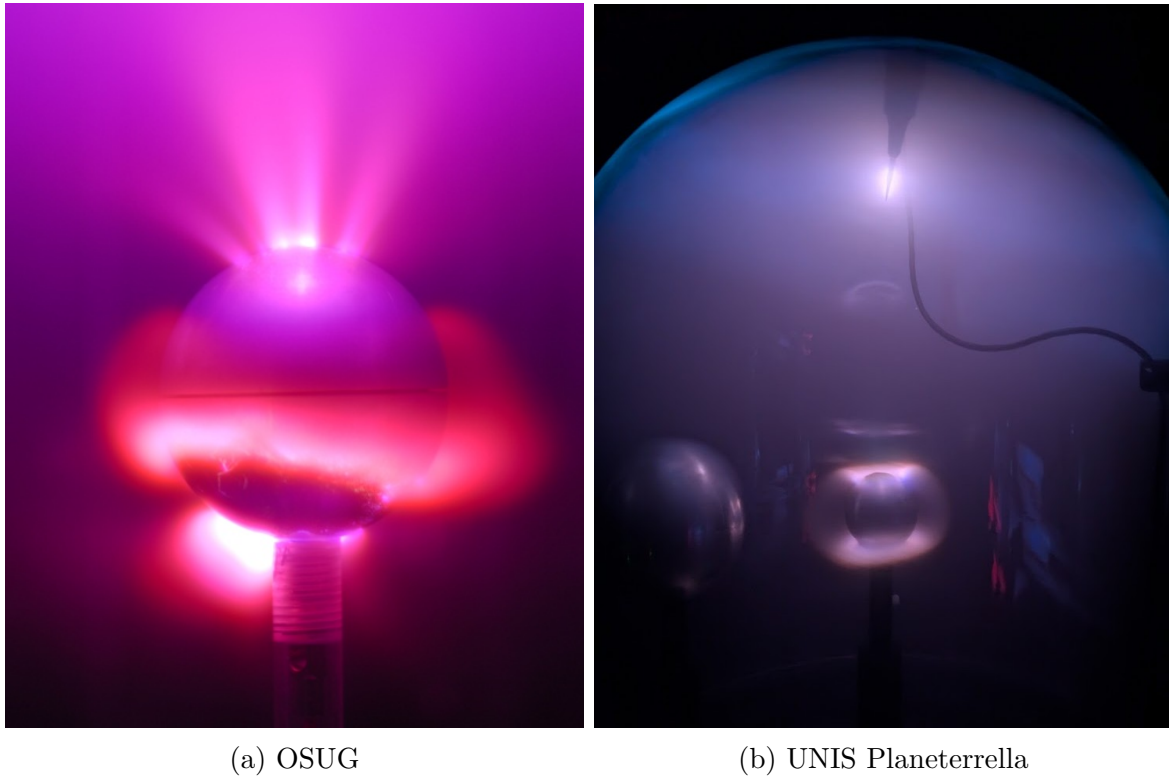


Figure 5.12: Uranus configuration. The left picture is from the OSUG website [25], and the right one is a picture of our Planeterrella in the same configuration.

5.2 BLUE CONTINUUM

While searching for ghost aurora and its associated continuous emission spectrum, we discovered that, at the lowest pressure settings (approximately 3 Pa), a blue glow was observed on the glass dome of the Planeterrella, see Figure 5.13, when used in the following configuration:

- Small sphere connected to the anode (+)
- Needle connected to the cathode (-), shooting electrons
- Lowest possible pressure: 3 Pa
- Highest possible voltage: plasma imposes 3 kV for these settings

This glow was particularly interesting for us, as it contains a very strong blue continuum that could help investigate the ghost auroras. Spectra of the glow are presented in Figure 5.14. This blue glow is extremely faint when a sphere is used as the cathode, and the continuum is only really measurable when using the needle. We can observe the blue glow covering the glass dome from the inside in Figure 5.13.

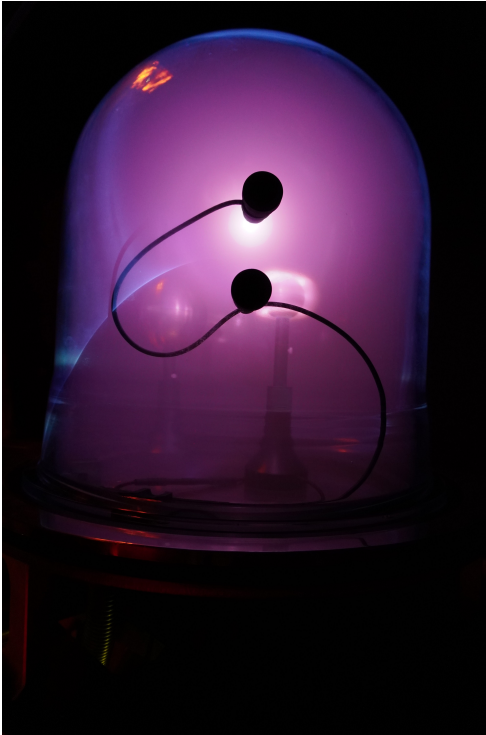


Figure 5.13: Blue glow covering the dome.

From this picture, we can already notice 3 important details. First, the blue glow seems to exist only in a very specific region of the Planeterrella, that is, an extremely thin region against the inside of the glass dome. Secondly, the blue glow seems to be repelled by the magnetic field originating from the permanent magnets used in the needle and cable support mounts. These magnets create "windows" that allow us to observe the usual plasma emission from the air inside the Planeterrella. As expected, spectral measurements through these windows don't contain the blue continuum emission. Finally, one can notice the projected shadow of the needle's cable on the blue plasma. The line crossing the shadow and the cable appears to perfectly intersect the tip of the needle. This would imply that the blue glow is directly linked to electrons emitted from the needle and travelling along nearly ballistic trajectories before interacting. Such a behaviour would be unusual for a conventional plasma discharge, where electrons are generally expected to undergo numerous collisions and diffuse through the plasma rather than preserving a direct path from the cathode.

Sharing this observation with the AurorAlpes community [2] revealed that several Planeterrella experimenters had previously encountered a similar blue glow with similar settings, although no explanation has yet been found. This blue continuum was particularly well documented in David Bernard's PhD thesis, chapter 7 [6].

To create the strongest possible blue glow, and thus the best measurement of the unknown continuous spectrum, we used external magnets to flip the needle over. This method produced a far brighter glow, as most of the electrons were directed to a small area of the glass over a short distance. One must be careful not to scratch the dome with the needle's tip, though, nor to put too much stress on the cable.

The results of the measurements are presented in Figure 5.14. The raw data showed that past 700nm, the blue glow was not noticeable anymore, and the spectra were similar to a regular N2 plasma one. Therefore, all the measured spectra were normalized to a reference, a measurement of the ambient purple plasma, by fitting an average of several strong N2 first positive and OI emission lines past 800nm. The results clearly show a bulge of continuous emission, particularly

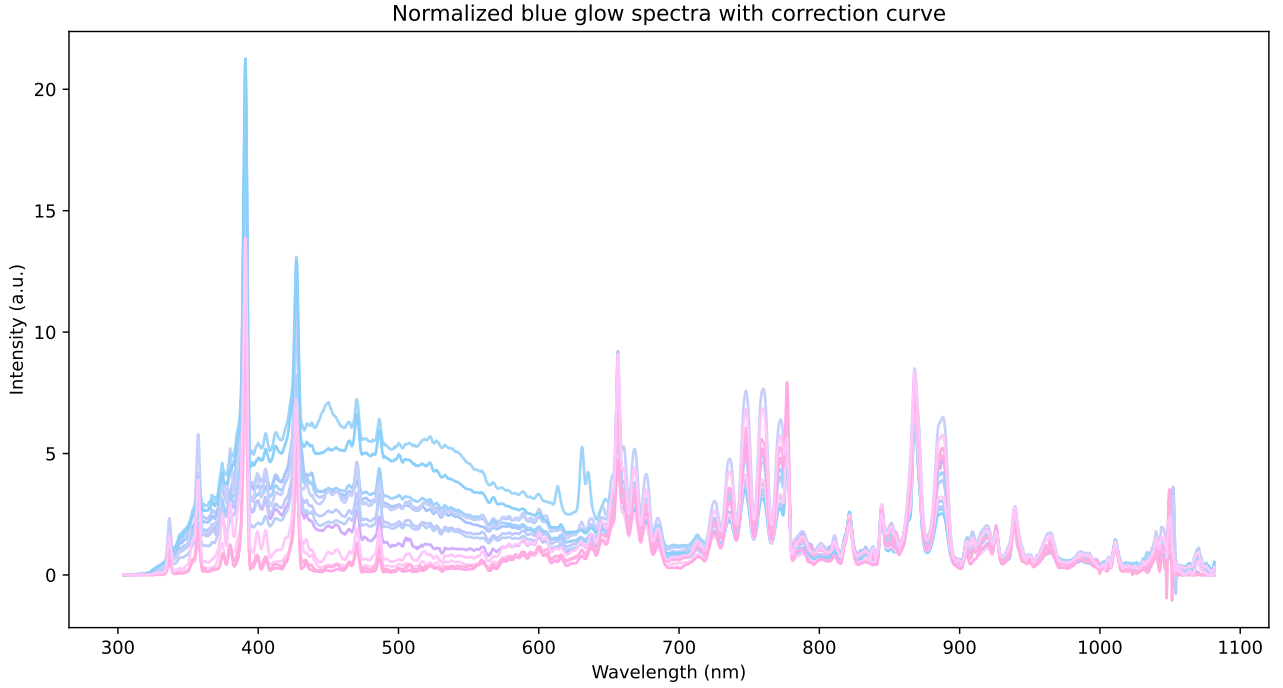


Figure 5.14: Spectral measurements of the blue glow and background pink plasma. The colours of the curves correspond to the real colour of the measured phenomena.

between 400 and 600 nm. This bulge is correlated to a visibly bluer plasma.

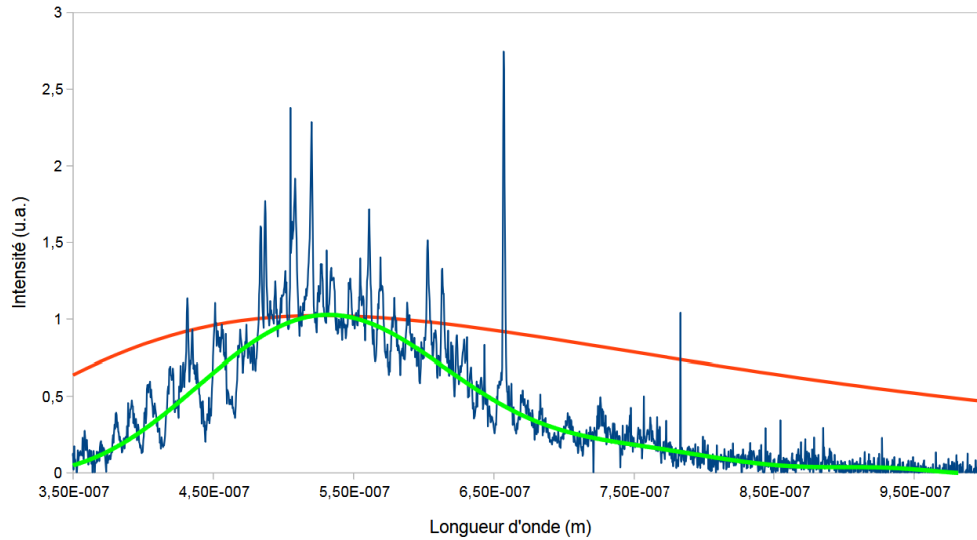


Figure 5.15: Blue spectrum measured by David Bernard taken from his thesis [6]. The green line is the signal envelope, whereas the red one is a 5500K black body emission spectrum.

The measured continuum spectrum (Figure 5.14) is similar to the one obtained by Bernard

Components	Content (percentage by weight)
SiO ₂	80,3
B ₂ O ₃	13,0
Al ₂ O ₃	2,4
Na ₂ O + K ₂ O	4,3

Figure 5.16: Composition of the glass dome, identifying it as borosilicate glass 3.3

(Figure 5.15). We can safely assume they are caused by the same phenomenon. A naïve explanation would be to consider this continuum to be caused by a blackbody emission. This seems unlikely, because the Planeterrella hosts a cold plasma where thermal equilibrium is not reached, meaning the ions and neutral species should be at around room temperature. Bernard proved this by comparing the shape of the blackbody emission and our measured spectrum. We went a step further by fitting the spectral line of the N₂⁺ First Negative (0-0) using PGOPHER, following the ideas in chapter 13 of Chemical Kinetics - Patel [29]. By comparing synthetic spectra at different temperatures with the measurements, the temperature of the N₂⁺ molecules close to the glass was estimated to be around 300K. So the blackbody emission is completely discarded.

Bernard claims this continuum is likely caused by a molecular spectrum, like the one of H₂ or other pollutants. While the presence of molecules other than N₂ and O₂ is certain, with the visible H-alpha line being proof of that, we believe the actual explanation to be different and somewhat more disappointing.

We propose that the continuum blue emission is **directly emitted from the glass itself** by a process called cathodoluminescence. Thanks to Olivier Katz, the manufacturer of our Planeterrella, we obtained the composition of the glass dome [33]. The composition is typical of a good-quality borosilicate 3.3. However, this manufacturer doesn't mention any potential light emission.

But another brand explicitly states that fluorescence is possible for borosilicate 3.3, although very dim [7]. They state, "Inherent fluorescence of BOROFLOAT® 33: Some materials have the ability to emit electromagnetic radiation after being activated by high-energy radiation. This property is referred to as fluorescence. It depends on the material's purity and structural characteristics as well as the radiation's excitation energy and excitation wavelength". Because their borosilicate is of the same composition as SIMAX's, we can safely assume this property transposes to our glass dome.

Sven Ebel et al. [12] provide a comprehensive atlas of the fluorescence spectra of various materials, including borosilicate glass (Figure 5.17). In particular, on page 12, section "common glasses", the cathodoluminescence spectra of Menzel coverslip, BK7, and pure SiO₂ are provided in Figure 5.17. BK7 has a percentage by weight wt% of Na₂O+K₂O of 15% and contains BaO, whereas Borosilicate 3.3 contains much less Na₂O+K₂O (around 5%) and no BaO. This changes the crystal structure of the glass quite significantly. The exact composition of the

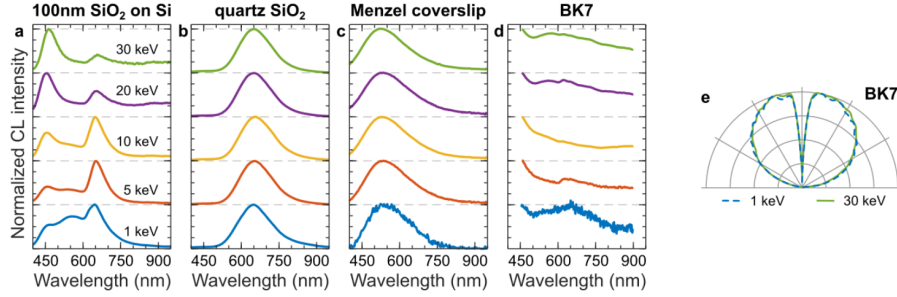


FIG. 12: CL of common glasses. Normalized CL spectra measured in a range of electron beam energies for: **a** 100 nm-thick layer of SiO₂ on bulk Si, **b** α -quartz (SiO₂), **c** Menzel coverslip, and **d** BK7 glass. **e** Isotropic angular radiation profiles of BK7 glass at 1 keV (dashed blue) and 30 keV (solid green), representative for all materials in panels **a-d**.

Figure 5.17: Fluorescence of common glasses, from Sven Ebel et al.,[12]. "Menzel coverslip" can be assimilated to our SIMAX borosilicate 3.3.

Menzel coverslip is not disclosed (trade secret), but it is a low-borate borosilicate with likely lower BaO content, getting it very close to the composition of our SIMAX borosilicate 3.3. The cathodoluminescence spectrum of the Menzel coverslip is very similar to the one we measured, with a strong blue continuum and a peak around 450nm. This strongly suggests that the blue glow we observed is indeed caused by cathodoluminescence of the glass dome, rather than a plasma emission phenomenon.



Figure 5.18: Aurora configuration and strong blue glow

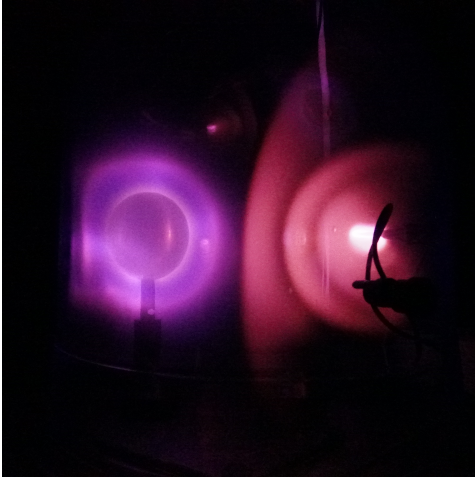
Chapter 6

Remarks

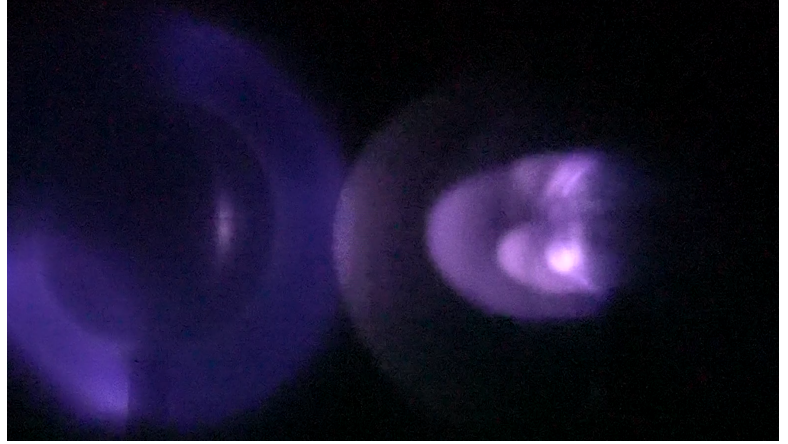
6.1 ETHANOL DOPING

The presence of ethanol in the Planetterella has a significant impact on the plasma emissions. It appears that injecting small amounts of ethanol into the chamber (either by direct injection through the air valve or after cleaning the chamber with alcohol) leads to stronger and brighter plasma emissions.

The presence of ethanol allows us to reach configurations that would otherwise be impossible to obtain with our power supply, such as the magnetopause or striation configurations. More generally, it creates intricate plasma forms beyond the usual reference configurations, mostly waves that visually appear to be emitted from the anode and travel towards the cathode. These waves can be either stationary or dynamic. The dynamic waves move slowly enough to be noticed by the human eye, they create a mesmerizing effect.



(a) Example of a stationary wave. Needle used as anode.



(b) Example of intricate dynamic plasma. Small sphere used as anode.

Figure 6.1: Unusual shapes obtained with ethanol doping. The waves are emitted from the anode.

Dyatko et al. [Dyatko2019] have shown that if the ionization energy of the admixture molecules is lower than the energy of the metastable state of the atoms, a small admixture of a molecular gas can lead to a reduction in both the breakdown voltage and the discharge operating voltage. Indeed, the ionization energy of ethanol is 10.48 eV [ethanol], which is lower than the energy of the metastable state of N₂ (11.1 eV). This means that the presence of ethanol in the chamber could potentially lead to a reduction in the breakdown voltage and operating voltage of the plasma discharge, resulting in stronger and brighter plasma emissions.

The spectral emission of ethanol lies outside the range of our spectrometer, deeper into the infrared. No direct emission lines of ethanol or CO₂ could be observed on top of the bright N₂ emissions. But the measured spectrum in presence of ethanol in Figure 6.2 still reveals an unusually high H_{α} line, which hints at the dissociation of ethanol molecules into hydrogen and organic molecules.

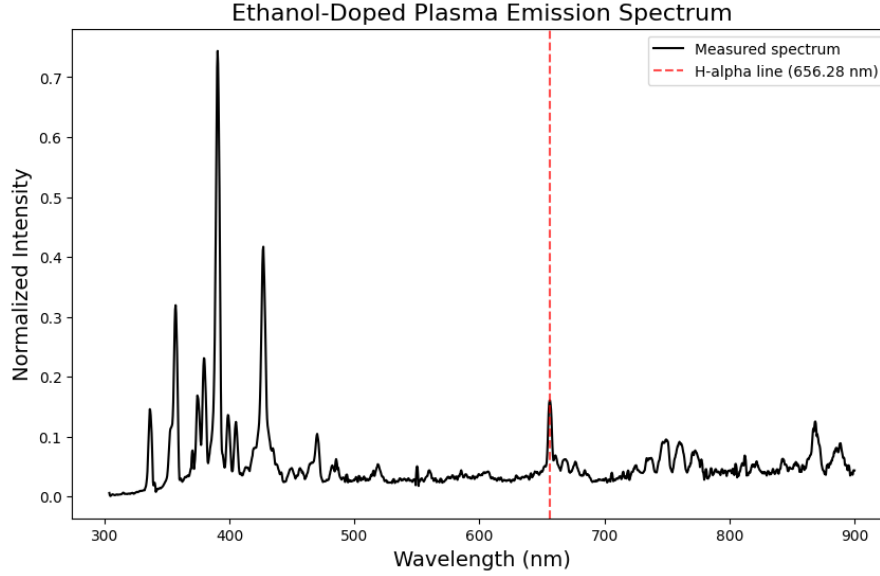


Figure 6.2: Ethanol doped plasma at 20Pa. Range limited to 300-900nm due to unexpected infrared pollution.

This effect would require further investigation to better grasp the influence of ethanol on the plasma emissions. But the most important takeaway is that the presence of ethanol boosts the plasma emissions, creating more electrons from a single supra thermal electrons. This effectively increases the current in the plasma, which would be equivalent to having a stronger power supply, allowing us to reach more configurations.

6.2 NEAR-INFRARED POLLUTION

In the dark, the majority of cameras are struggling to focus, especially when aimed at blurred plasma. The newest models now include a Vertical-Cavity Surface-Emitting Laser (VCSEL for short), which is a small infrared laser that helps the camera focus in low-light conditions. This laser typically emits at around 940nm, as mentioned by SAMSUNG [SAMSUNG2023], but some models emits at 850nm. Taking a spectral measurement while recording with such a camera could therefore lead to a strong peak at 940nm, as shown in Figure 6.3. It is important to not mistake this peak for a plasma emission line.

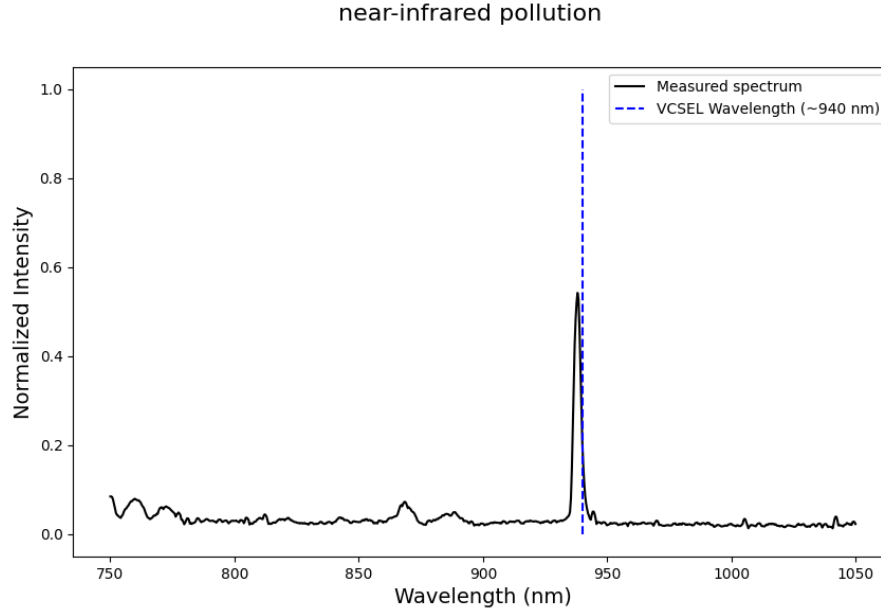
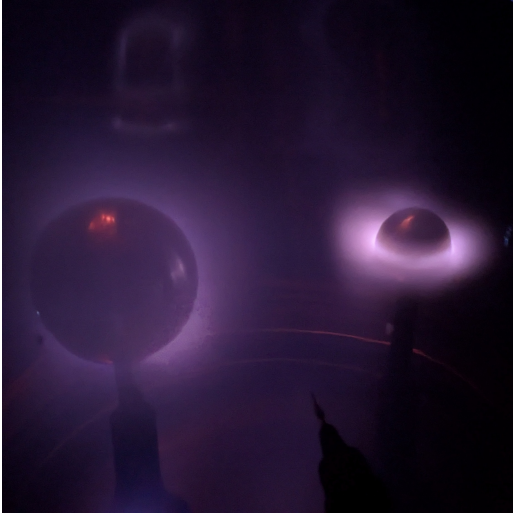


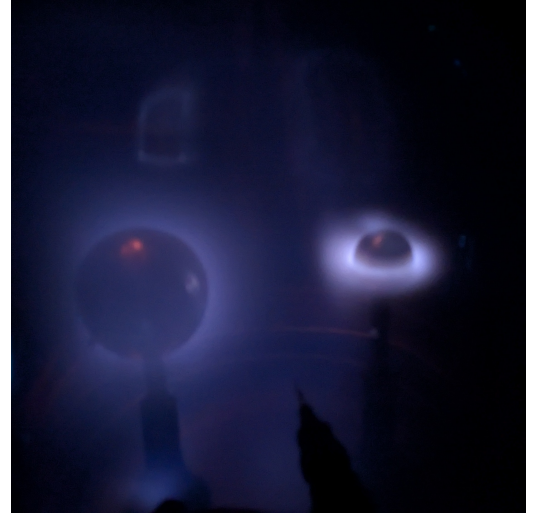
Figure 6.3: Near-infrared pollution due to VCSEL.

6.3 TIME EVOLUTION

Even though we believe Bernard [6] was measuring cathodoluminescence instead of plasma emission, his observation on the plasma remains: the plasma becomes visibly whiter over time when in the lowest pressure settings. This phenomenon has also been observed in our Planeterra. Letting the vacuum pump run for 30 minutes and then turning the Planeterra on would lead to the plasma evolving from the usual pink/purple colour to a cloudy white colour in about 3 minutes. The difference is presented in Figure 6.4. Although the camera exaggerates the blueness of the plasma on the second picture; it is interesting to see that fixing the colour balance of the camera reveals a colour evolution.



(a) Initial colour of the plasma



(b) Colour after 5 minutes (Camera exaggerates blueness)

Figure 6.4: Colour transition in the Planeterrella at 5Pa with same camera settings.

Spectral measurements have been made at constant time steps to measure the time evolution of the plasma, presented in Figure 6.5. We can notice a continuous intensity increase in the range 400 to 700 nm. This could be linked to the cathode luminescence effect; its continuous emission would be much fainter than in the previous section because we are using the large sphere as the cathode instead of the needle. But this wouldn't explain why specific regions change more than others. Indeed, we can notice a line appearing between 505 nm and 515 nm. We can also notice a diminution in intensity of the strongest lines, mainly N_2^+ first positive, atomic H, and atomic O. This indicates that the plasma takes a few minutes to reach its emission equilibrium at this pressure. Further work could be done on this phenomenon, but in these conditions, the plasma is faint and evolving rapidly, making it difficult to measure the time evolution accurately.

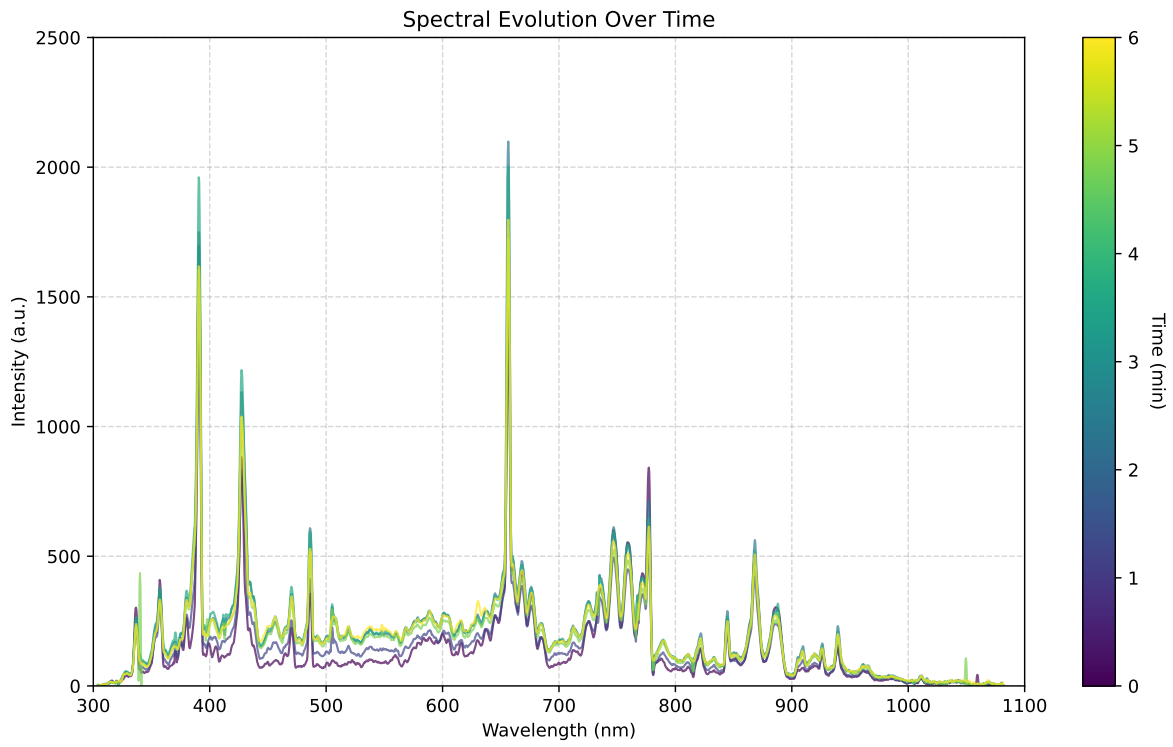


Figure 6.5: Spectral time evolution at 5 Pa.

Chapter 7

Conclusion

This thesis combined experimental spectroscopy and numerical modelling to characterise the optical emission of the UNIS Planetterella and the electron dynamics behind it.

Experimentally, all canonical configurations were reproduced, and calibrated spectra were obtained for the auroral oval and coronal expansion configurations across 300-1100 nm, extending previously available data. This required a full instrumental calibration, including a blackbody-extended flat-field correction into the near-UV. The key results are the identification of a previously unexplained blue continuum, observed at the lowest pressures with the needle cathode, and valuable information about the different Planetterella configurations that could be used as documentation for the next users.

Numerically, an electron-trajectory model was redesigned to be more flexible, using an object-oriented architecture with a Boris pusher replacing the original Runge-Kutta integrator. This model reproduced two observed features: the asymmetric bulge in the auroral oval configuration, and the longer electron residence time and denser collision pattern of the stellar ring configuration.

These results support the Planetterella's value as a genuine laboratory analogue for solar and magnetospheric phenomena, allowing for the manipulation of plasma with remarkable ease. However, some limitations remain. The Planetterella would really benefit from a magnetically-mounted Langmuir probe for direct plasma diagnostics. The simulation could benefit from quenching physics in the collision engine to predict relative line intensities, or even a Particle-in-Cell treatment of the electric field to resolve Debye screening.

Appendix A

Spectra

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