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Laboratory Experiments Confirm the Polarization of Auroral Emissions

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Key Points:

- We reproduce in confined laboratory conditions the auroral blue and purple ionospheric emissions
- The Degree of Linear Polarization depends on the magnetic conditions and is similar to that observed in the aurorae
- We conclude that part of the observed auroral lights polarization is created at the emission

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract A series of experiments have shown recently that several auroral lines are polarized, when observed from the ground. However, this polarization may be caused by indirect light sources (from the ground or the sky) scattered in the lower atmosphere by Rayleigh and Lorenz-Mie scattering, or during the crossing of the ionospheric current sheets. Here, we present polarization measurements of the N_2^+ blue (427.8 nm) and purple (391.4 nm) emissions in a laboratory confined setting that excludes any light pollution or scattering. We show that both lines are polarized, at a level comparable to that of the natural auroral observations. Our results furthermore show that the Degree of Linear Polarization depends on the magnetic conditions. This set of experiments confirms in a controlled environment the polarization of auroral emissions and constitutes a strong evidence in favor of auroral emission already polarized in the upper atmosphere.

Plain Language Summary We prove through a laboratory experiment the existence of the auroral polarization. We also show that this polarization is created at the emission itself and not during its travel through the atmosphere.

1. Introduction

The question of the auroral polarization was first addressed early in the twentieth century (Harang, 1933). The first observation was performed during the International Polar Year by Duncan (1959) who found a Degree of Linear Polarization (*DoLP*) up to 30%. This value was rapidly challenged, Chamberlain (1959) and Harang (1960) claiming that it could only be due to experimental artifacts, because of the depolarizing collisions. The topic was then closed until 2006, when a new dedicated facility allowed to reconsider it (Lilensten et al., 2006). The first modern observation targeted the red atomic oxygen line (at 630 nm) in the polar cusp, showing a *DoLP* up to 10% and an average value of ≈5% during auroral quiet times. The *DoLP* was found to decrease during strong auroral events, which was interpreted as the role of the depolarizing collisions. A set of further experiments (Lilensten, Bommier, et al., 2015, and references herein) allowed to better characterize this polarization, showing that the Angle of Linear Polarization (*AoLP*) was related to the orientation of the magnetic field at the altitude of emission (around 220 km for the red line).

Observing the auroral polarization was then considered as a potential way to indirectly sample the ionospheric environment. A new instrument was conceived in order to observe other auroral emissions, and Bosse et al. (2020) showed that the oxygen green line (557.7 nm) emitted in the ionospheric E-region around 110 km is polarized when observed from the ground, in spite of theoretical predictions against it (Bommier et al., 2011). Two other emission polarizations were also discovered, namely the purple (391.4 nm) and blue (427.8 nm) emissions of the 1^{st} N_2^+ negative band originating typically between 85 and 90 km altitude (see also Barthelemy et al., 2019).

However, light pollution scattering in the lower atmosphere is also polarized, and might contribute significantly to the observed polarization. A first attempt to disentangle the contribution of light scattering and ionospheric emissions was conducted by Bosse et al. (2022) by combining field measurements and polarized radiative transfer modelization. They show that scattering in the lower atmosphere cannot be fully neglected while it also cannot fully explain the observations. They conclude that polarization at the emission is necessary.

Two assumptions remain to explain the source of polarization in the ionosphere: the emission is intrinsically polarized or the light emitted is unpolarized and polarization occurs during the crossing of the upper atmosphere,

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through the Hall and Pedersen conductivity layers. The first explanation has already been explored in different gases such as Barium, Calcium, Mercury (Fano & Macek, 1973; Skinner et al., 1927) in laboratory experiments and theoretical models. However, no study about the N_2^+ auroral emissions could be found.

In this paper, we attempt to reproduce the auroral observations in laboratory confined conditions with no light pollution (direct or indirect through reflection) nor atmospheric scattering. If polarization is observed, then it supports a polarization of ionospheric emissions in the upper atmosphere. On the contrary, if no polarization is detected in the absence of light pollution sources, then all previous auroral measurements are mostly influenced by light pollution scattering in the lower atmosphere. The experimental setup is described in Section 2. We present our results in Section 3, and finally present in Section 4 the main perspective they lead to.

2. Experimental Setup

The full experimental setup is shown in Figure 1. It consists in an auroral simulator, the *Planeterrella* creating the emissions, and a polarimeter, *Grand Cru*. Both are described thereafter.

2.1. The Planeterrella

The Planeterrella is an auroral simulator (Lilensten et al., 2013, 2014) partly based on Birkeland seminal Terrella experiment. It consists in a 50 L vacuum chamber where two spheres (of respectively 10 and 5 cm diameter) and an electric duct are installed. The spheres are movable and may rotate in the horizontal plane along the vertical axis. In the following, one rotation is made every $T_o = 4$ s. Inside the spheres, mobile magnets are installed with a magnetic field of 400 mT each. Any of these (spheres or duct) can be connected to the anode or the cathode of an electric generator. The Planeterrella has already been used for scientific purposes: to study the auroral formation and plasma interaction between magnetized objects (Gronoff & Simon Wedlund, 2011), and to demonstrate the existence of blue aurorae in the Martian atmosphere (Lilensten, Bernard, et al., 2015) due to CO_2 emissions.

The main physical parameters inside of the Planeterrella are computed in Lilensten et al. (2009). We provide the characteristic values of the current setting in the Supporting Information S1. We find that the beam electron temperature, velocity and densities are much higher than the suprathermal values in the E-region ionosphere computed in Marif and Lilensten (2020). Compared to the E-region ionosphere, the Planeterrella suprathermal velocity, temperature and density are about 400, 10^3 and 10^6 times larger, respectively. This results in an estimated current magnitude maximizing at about 0.8 $A.m^{-2}$ in front of the sphere facing the polarimeter. Over the approximate one cm width of the current in the Planeterrella, the integrated current comes to $\approx 3 \times 10^{-4}$ $A.m^{-1}$. This is negligible compared to the currents in the conductivity E-region layer which is typically of the order of a few tenths of $A.m^{-1}$ in auroral regions (Kelley, 2009; Olsen, 1997; Laundal et al., 2016, 2018).

In the present setting, the Planeterrella is used with only the electric duct as the electron gun (cathode) and the 10 cm sphere as the receiving target (anode) where aurorae are produced. A series of black caches was inserted inside the vacuum chamber in order to prevent any reflection from penetrating the vacuum chamber. Finally, a thick cover sheet was installed all over the Planeterrella—Polarimeter system to hide any potential light pollution. The gas in the chamber is simply made of ambient air (roughly 80% N_2 and 20% O_2). Any attempt to introduce atomic oxygen would result in a failure as, in such a small confined volume, it would immediately reconnect as molecules. Our comparison with the upper atmosphere is therefore reduced to the N_2^+ emission lines, that is, at 391.4 and 427.8 nm. The choice of the pressure and the voltage depends on the Paschen's law (Paschen, 1889). In order to avoid power outage, we use a pressure of about 5 Pa and a voltage of 1.6 kV.

2.2. The Polarimeter

To measure the polarization of the light emitted by the Planeterrella, we use the same polarimeter (called *Grand Cru*) as that used in a previous study on the auroral polarization. A detailed description is provided in Bosse et al. (2020), with the instrumental characteristics and the data analysis procedure. We therefore only recall here its basic principles and the main instrument design.

The light first passes through a polarizing filter rotating regularly at 5 rotations per second. We then select the wavelength of interest with an optical filter of 10 nm width. Finally, a photomultiplier measures the remaining

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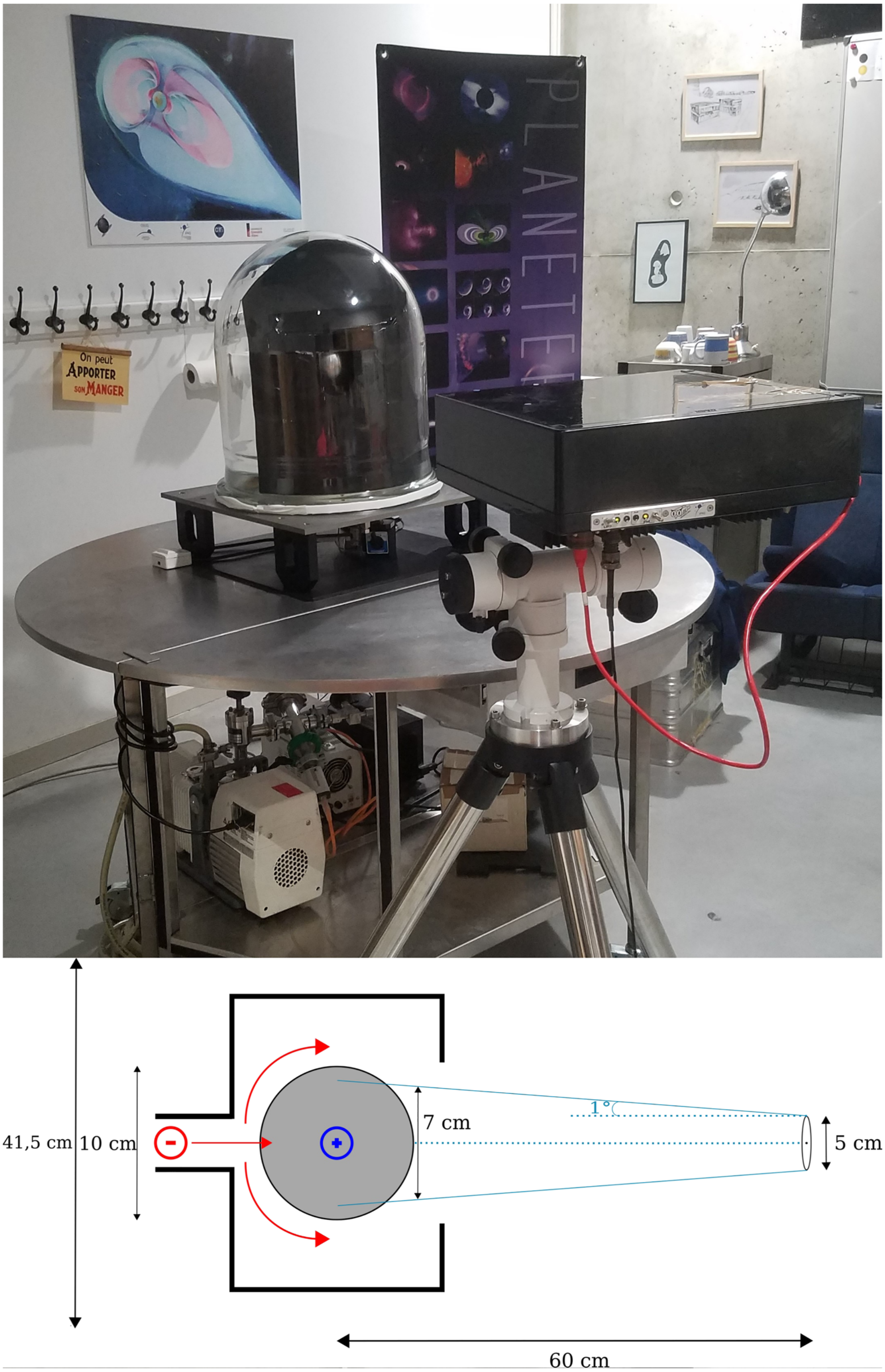

Figure 1.

signal. If the incident light is polarized, the flux measured by the photomultiplier will vary depending on the orientation of the polarizing filter. The variations of the signal then follow Malus law, and over one rotation of the polarizing filter we can retrieve the main polarization properties of the light: the incident flux, its *DoLP* and

AoLP. It is also possible to average the signal over multiple rotations of the polarizing filter to increase the S/N ratio. However, this assumes that the signal is constant over the averaging window T_1. We use here data averaged over $T_1 = 10$ s $\ll T_0$. *Grand Cru* was calibrated in *DoLP* and *AoLP*, but not in flux. This is not an issue here since we focus on the polarization parameters. The *DoLP* of the instrument was confirmed using a dedicated calibration facility at the Laboratoire d'Optique Atmosphérique (LOA) in Lille (France). It is able to measure accurately polarization rates as low as 1%.

The optical system of the instrument has a 2° opening angle, and a 5 cm diameter. This diameter is negligeable when observing the nightglow in the upper atmosphere, at least 90 km away. In the laboratory, it was installed at about 60 cm of the Planeterrella, in order to prevent from any scattering on atmospheric aerosols, while receiving enough light flux for a proper detection of the *DoLP*. In this configuration, we obtain an observing surface of ≈7 cm diameter on the emitting sphere (see Figure 1). As a consequence, we cannot focus on a dedicated area close to the sphere: our measurements average emissions over the full visible area, that is, a range of magnetic field lines will appear in the field of view. *Grand Cru* has four independent channels of which only two are used in this work. One is dedicated to the purple line and another one to the blue one. However, the polarimeter is too close to the Planeterrella, so that only one channel can observe at once.

2.3. Choice of the Vacuum Chamber

The calibration was performed in atmospheric pressure conditions using a plasma lamp filled with Ar at low pressure. Argon has an emission line at 392 nm, that is, falling within the bandwidth of our purple filter. Two vacuum chambers have been tested, one in glass and one in Plexiglas. We introduced a polarizing sheet between the emitting lamp and the vacuum chamber. Its transfer efficiency measured without the vacuum chamber results in an observed polarization rate of 98.3%. With the glass chamber, this value increases to 98.4%, that is, within the experimental error bars. The Angle of Linear Polarization remains the same with and without the glass chamber. With the Plexiglas chamber, the polarization rate decreases down to 94.7% while the angle remains unchanged. The results shown below are all made with the more reliable glass chamber.

3. Results

A series of experiments was conducted with a large set of configurations (varying the pressure, magnet properties and orientations, relative positions of the electric duct and the sphere, different caches, different rotation velocities…). Some of them are shown in the Supporting Information S1. We also performed measurements with and without rotation of the sphere. The idea behind is that if the polarization is linked to the magnetic field, it should show a cyclical pattern from a rotation to another.

We focus below on a selection of significant results, with the sphere rotating at a period $T_0 = 4$ min, and a 5 Pa pressure. We first show in details two measurements in the blue line obtained with and without a magnet inside of the sphere. We will then give the equivalent polarization parameters for the purple line. None of the other observations contradicts the ones presented here.

3.1. No Magnet, 427.8 nm Emission Line

We first show the results when no magnet is inserted inside the sphere. In this configuration, the electrons are simply driven by the electric field between the cathode and the anode. This homogeneous configuration should result in a stationary signal.

In Figure 2 (left panels), we show the light intensity (in arbitrary units), the *DoLP* (in %) and the *AoLP* (in degrees). Black dots correspond to the raw data. The blue lines represent data processed over $T_1 = 10$ s (i.e., 50

Figure 1. Picture and diagram of the setup. In the picture foreground: the polarimeter *Grand Cru*. We only use two of its four channels, one at a time, for observing the polarization at 391.4 nm (purple) and 427.8 nm (blue). In the picture background (on the table): the vacuum chamber. Inside, the sphere is surrounded by a black cache in order to avoid any internal reflection on the glass chamber. Below the table, a vacuum pump creates a primary vacuum of about 5 Pa. One generator injects electric current in the Planeterrella while a second one is used to make the sphere rotate on itself with a period $T_0 = 4$ min. During operation, the room is fully dark and a thick cover sheet wraps the full setup in order to prevent any external light pollution. The diagram (not to scale) shows the main dimensions and the geometry of the experimental setup. One channel of the instrument (on the right), is pointing toward the Planeterrella through the glass chamber (thin circle) and then the hole in the black cache (thick line). Inside the vacuum chamber, the electrons are produced at the cathode (red minus sign), and move toward the anode sphere (blue plus sign).

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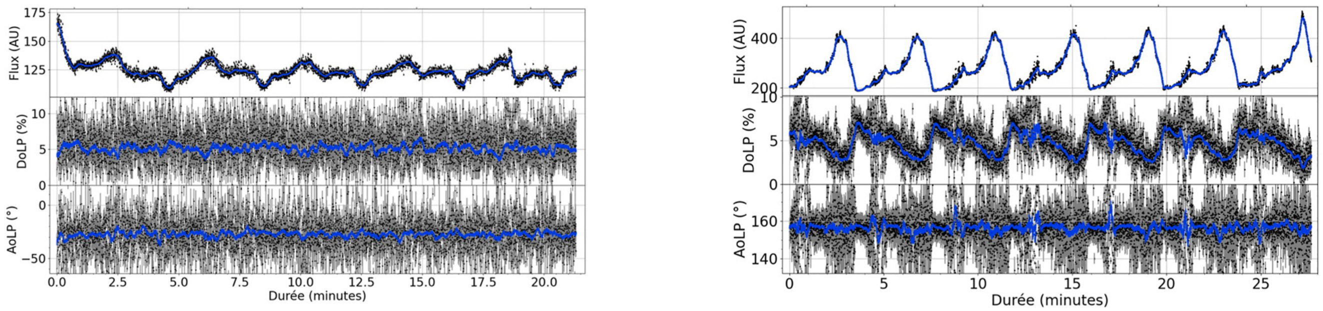

Figure 2. Polarization parameters at 427.8 nm. Upper panel: light intensity in arbitrary units. Middle panel: Degree of Linear Polarization in %. Lower panel: Angle of Linear Polarization in degrees. Left panels: without a magnet inside the sphere. Right panels: with a horizontal magnet inside the sphere. Uncertainties on the raw data (black dots) are indicated by the gray shaded area. Uncertainties on the data after averaging over T_1 are given by the width of the blue curve.

rotations of the polarizing lens). Once averaged over the whole observation period $D \approx 21$ min, we obtain the following values: $I = 124$ AU; $DoLP = 5,1\%$ and $AoLP = -28°$. There is a small variability of the intensity (about 20%) due to the inhomogeneity of the sphere and the positioning inaccuracy of the instrument. As expected, both the polarization rate and angle are overall steady throughout the rotations, the *DoLP* varying between 4% and 6% and the *AoLP* varying between −20° and −35°. Furthermore, their observed variations do not exhibit the repeating pattern corresponding to the rotation frequency of the sphere. The *DoLP* and *AoLP* thus can be considered constant throughout the observation. The value of the polarization rate is in the same range as that observed in real aurorae (Bosse et al., 2020). As expected, in the absence of a magnet, the rotation of the sphere only weakly affects the observed polarization properties.

3.2. Horizontal Magnet, 427.8 nm Emission Line

We place the magnet horizontally inside the sphere, such that its magnetic poles face the polarimeter twice per rotation, with magnetic lines parallel to the line of sight, while the magnetic equator also faces the polarimeter twice per rotation, with magnetic field lines perpendicular to the line of sight. We show the results with a horizontal magnet in Figure 2 (right panels).

After averaging over the entire observation duration, we get $I = 282$ AU; $DoLP = 4.4\%$ and $AoLP = -24°$ (or 156° when accounting for the 180° congruency). The *DoLP* value has the same order of magnitude as without a magnet. However, the rotation period of the sphere is now clearly visible on the flux and the *DoLP*. The maximum intensity at about 400 AU (twice the minimum) occurs when one pole faces the polarimeter. The secondary maximum around 270 AU occurs about 2 mn apart when the second pole is in front of *Grand Cru*. The times when the equator faces the polarimeter are marked with a minimum at about 200 AU and a secondary minimum around 255 AU.

The *DoLP* fluctuates between 2.5% and 7.5% in a periodic manner. The time elapsed between two maxima of the *DoLP* is about 4 min, corresponding to the rotation period of the sphere. A secondary maximum occurs in the intensity and the DoLP 2 minutes after the maximum. Should the magnets be exactly identical, these maxima should be at equal levels. However, the magnets (neodymium, N42, from commercial industry) are not intercalibrated, therefore the differences. These variations of the *DoLP* are anti-correlated with the fluctuations of the light intensity over one rotation, as already observed in geophysical auroral conditions (Bosse et al., 2020; Lilensten, Bommier, et al., 2015). Indeed, the peaks of intensity around 400 AU are aligned with the drops of *DoLP* at 2.5% and, reversely, the drops of intensity at 200 AU correspond to the peaks of *DoLP* around 7.5%. However, the *DoLP* being the ratio between the polarized and non polarized parts of the total emission, it is unlikely to depend only on the intensity itself. We therefore conclude that these variations in the *DoLP* result from an effect of the magnetic field.

The *AoLP* still remains relatively steady, varying between −30° and −12°. Because of the relatively large aperture of the instrument (about 5 cm, see Section 2.2), it is hazardous to relate this value to isolated magnetic field lines. Still, a slight effect of the rotation shows up, with a variation of about 10° when a pole faces the polarimeter.

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3.3. 391.4 nm Emission Line (Purple)

The patterns observed in the purple line are very similar to these of the blue line. This is not surprising as both are due to the same excitation level, that of the 1^{st} N_2^+ negative band. We therefore do not show them in detail here (see the Supporting Information S1), and only recall the main values:

- Without a magnet in the sphere, the intensity and the polarization parameters are stable, with average values (over the whole observation period) of $I = 46$ AU (from 39 AU to 56 AU); $DoLP = 3.2\%$ (from 2.5% to 4%) and $AoLP = -23°$ (from $-37°$ to $-8°$). The low value of the intensity compared to that observed for the blue line is probably due to the transfer function of the glass and to a difference in the photomultipliers sensitivities on both observing lines (blue and purple), but this assumption could not be properly tested. We note that the *DoLP* observed in the purple line is lower than that in the blue line. This could carry some insight on the atomic properties of the emissions, but it may also be due to inaccuracies of the experimental setup (e.g., variations in the pointing direction of the instrument, or of the pressure, might explain this difference).
- With a horizontal magnet, the average values are $I = 63$ AU (varying from 32 AU to 108 AU), $DoLP = 3.2\%$ (from 2% to 5%) and $AoLP = -20°$ (from $-32°$ to $-11°$). In this emission line too, the rotation clearly impacts these values. The intensity triples over one rotation of the sphere, and the *DoLP* variations are stronger and clearer, with a maximum occurring when looking straight to the equator. However, the *AoLP* is more stable than that observed with the blue line, hardly showing an effect of the rotation.

3.4. Comparison With Real Auroral Observations

The same lines have been observed in auroras (Barthelemy et al., 2019; Bosse et al., 2020, 2022). The average *DoLP* was evolving between 1% and 5% in the blue line, and up to 6% in the purple. The purple observations were more stable than the blue ones. In both cases, we also observed that the intensities of the emissions were correlated with the electron density variations recorded with the Incoherent Scatter radar EISCAT (Bosse et al., 2020) and that the *DoLP* varied accordingly to the magnetic variability, especially in the blue. For both the purple and the blue lines, the magnitude of the *DoLP* measured in laboratory conditions is similar to that observed in auroral geophysical conditions.

4. Conclusion

With this experiment, we aimed at reproducing in controlled and confined conditions the observations made in auroral conditions at high latitudes (Barthelemy et al., 2019; Bosse et al., 2020, 2022), in order to check whether the polarization observed from the ground is created in the upper atmosphere at the emission, or during the crossing of the light through the current ionospheric layer, or by light pollution and scattering in the lower atmosphere. The experimental setting prevents from any external pollution light, from the internal reflection on the glass chamber and from diffusion on aerosols. We could observe the 1^{st} N_2^+ negative band emissions in blue (427.8 nm) and purple (391.4 nm). Both are clearly polarized when no magnet is inserted in the sphere with a polarization rate very close to that observed in the ionosphere. When a magnet is inserted inside of the sphere, the polarization parameters are strongly conditioned by the magnetic field configuration with respect to the polarimeter.

We conclude that the polarization depends on the direction of the electron flux (or of the current in the upper atmosphere) since the electron path is driven in this case by the magnetic field lines. This is in agreement with the results found in the upper atmosphere by (Bosse et al., 2020, 2022) and therefore confirms that these observations are not only due to the auroral light scattered during the lower atmosphere crossing, nor to light pollution. However, we failed in determining the exact *AoLP* because of a too wide field of view, merging too many magnetic field lines, even if a slight effect of the rotation is seen in the blue line *AoLP* (but not in the purple one).

To better address this last issue, we must reduce the field of view of the polarimeter's lenses. We also need to improve the experimental system by regulating pressure in a stable and highly accurate manner in order to perhaps explain the sharp intensity fluctuations observed when the pressure is fixed at an approximately steady value.

The second question is whether the polarization occurs at the emission or during its crossing of the conductivity layer. In order to address this question, we compute an integrated current magnitude maximizing at 3×10^{-4} $A.m^{-1}$ between the sphere and the polarimeter (see Supporting Information S1). This corresponds to the current within the electron beam that spreads over the full surface of the sphere. This value is negligible when compared to the current density in the upper atmosphere (0.3 A.m^{-1} in auroral regions (Kelley, 2009; Olsen, 1997; Laundal et al., 2016, 2018)). We therefore conclude that the polarization is created at the emission in the Planeterrella. Since the *DoLP* values observed with the Planeterrella in front of the sphere, facing the polarimeter are very much comparable to that in the upper atmosphere, we conclude that, the polarization in the ionosphere is likely generated directly at the emission.

However, we do not propose a more detailed explanation of the polarization origin yet, other than that it must be linked to the collimated impacting electron flux and to the local electro-magnetic environment at the emission. Future works should focus on developing our understanding of the polarization origin in the upper atmosphere. We propose three research axes: theoretical work on the atomic physics at play, multi-instrumental observations of the auroras to link the polarization to other ionospheric quantities, and further laboratory experiments with an improved setup. The first two ideas are already in the making and will be discussed in future publications. Improving laboratory experiments request a dedicated facility in order to reduce the difficulties of the measurements, to focus on smaller areas of the emitting surface so as to better distinguish the effect of the magnetic field. For example, one could use a smaller chamber, within a uniform magnetic field throughout the full volume and a uniform electron flux crossing from one side to the other, so as to distinguish the effect of the electric current. An electromagnet will soon allow to vary the magnetic field intensity and study its effect, in particular to determine whether a threshold is at work.

This laboratory work confirms that observing the polarization of the upper atmosphere emissions is a new way to access the electromagnetic environment (magnetic field variations, electric fields …). The blue and purple lines are emitted in the lower Eregion. The oxygen green line is emitted around 110 km and the red one around 220 km (i.e., Rees (1963) and references herein). Our investigations may open a way to monitor the ionosphere—thermosphere system at different altitudes.

Data Availability Statement

The instrumental data used and described in this study are available on the PerSCIDO platform maintained by the University Grenoble Alpes (https://doi.org/10.18709/perscido.2021.11.ds356). We provide the complete raw and processed data, as well as a plot representation for each observation and a comprehensive README file for their usage.

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