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Polarization in aurorae: A new dimension for space environments studies

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[1] The polarization of emission lines is a noteworthy observational parameter in astronomy. However, it has never been detected without ambiguity in planetary upper atmospheres. Theoretical considerations have suggested that the polarization of the thermospheric oxygen red line (630 nm) could exist in the polar cap region. We present here its first successful measurement at Svalbard in January 2007, during active geophysical conditions. We assign its origin and variability to complementary effects between permanent low-energy electron precipitation and sporadic auroral events. Implications in physics, geophysics and planetary science are foreseen. In physics, it raises the question of the polarization of a forbidden transition by electron impact which is still unknown. In geophysics, it provides a new parameter to constrain the thermospheric models. In planetary science, it makes it possible to derive the local configuration of the magnetic fields. It therefore opens new perspectives for future space missions towards other planets. **Citation:** Lilensten, J., J. Moen, M. Barthélemy, R. Thissen, C. Simon, D. A. Lorentzen, O. Dutuit, P. O. Amblard, and F. Sigernes (2008), Polarization in aurorae: A new dimension for space environments studies, *Geophys. Res. Lett.*, *35*, L08804, doi:10.1029/2007GL033006.

1. Introduction

[2] Light is described through three basic parameters: wavelength, intensity and polarization. The latter is more difficult to apprehend because human eyes are polarization blind. Its existence is conditioned to the anisotropy of the excitation or transmission processes. During the 1958 International Polar Year, *Duncan* [1959] reported on possible polarization during one aurora at middle latitude. Shortly after, *Chamberlain* [1959] argued against the validity of the result. The topic was then considered closed and the belief remained that collisions would prevent any polarization of thermospheric emissions.

[3] In spite of this commonly shared belief, we reconsidered the question [*Lilensten et al.*, 2006]. Our analysis showed that Duncan was correct in underlining (1) that in the Earth's upper atmosphere, the magnetic field drives the incoming charged particles, creating the conditions necessary for a polarized emission and (2) that the intense atomic oxygen red line triplet emission (630.0, 636.4 and 639.2 nm) peaking around 220 km, is a promising candidate for detection of linear polarization. Moreover, since the 1950's, quantum mechanics considerations have shown that even forbidden transitions may be polarized, although the process is still not understood [*Kazantsev et al.*, 1999].

[4] From this analysis, we concluded that the polarization occurrence should increase when the energy of the incoming particles is relatively homogeneous and up to a few eV above threshold (1.96 eV). Precipitated electrons must have energies of a few hundreds eV at about 600 km so that they are cooled down to a few eV in the region of the red line emission. Such electrons are found in auroral precipitation [*Rees*, 1989] and are permanent in the polar caps (the region surrounding the magnetic poles) where the solar wind is convected along the magnetic field lines, creating the spatially and energetically homogeneous polar rain [*Winnigham and Heikkila*, 1974; *Newell and Meng*, 1990]. Recently, we revisited this question [*Lilensten et al.*, 2006] and measured the oxygen red line polarization in favourable conditions which led to the present discovery.

2. Experiment

[5] We installed a dedicated photopolarimeter at Longyearbyen, Svalbard (78.20 N, 15.83 E geographic, 75.27 N, 111.92 E geomagnetic). It includes two detection channels with identical photomultipliers, front lenses and 630.0 ± 1 nm interference filters. A linear polarization filter rotates in front of channel 1 with a 4.02 s period and with 20 points per second sampling rate. This rotation period was chosen by considering the natural life time of the O^1D state (110 s). The modulations had to be small with respect to this time and the design of a device with front optics rotating in four seconds was technically feasible for an instrument that was to be operated under harsh conditions. Full extinction of horizontal polarization occurs at 0° and 180°. The aperture is 2°.

[6] Two measurement campaigns were performed: December 10–19, 2006 and January 16–18, 2007. The first campaign was used for calibration and quantification of the noise level which was found to be smaller than 2% when the photomultipliers were thermally stabilized. The main source of noise is indeed depending on the outside air thermal variations once instrument temperature equilibrium is reached.

[7] The geophysical activity remained enhanced from January 15 to 21. The moon was dark, with an elevation larger than that of the sun (see below). The temperature was

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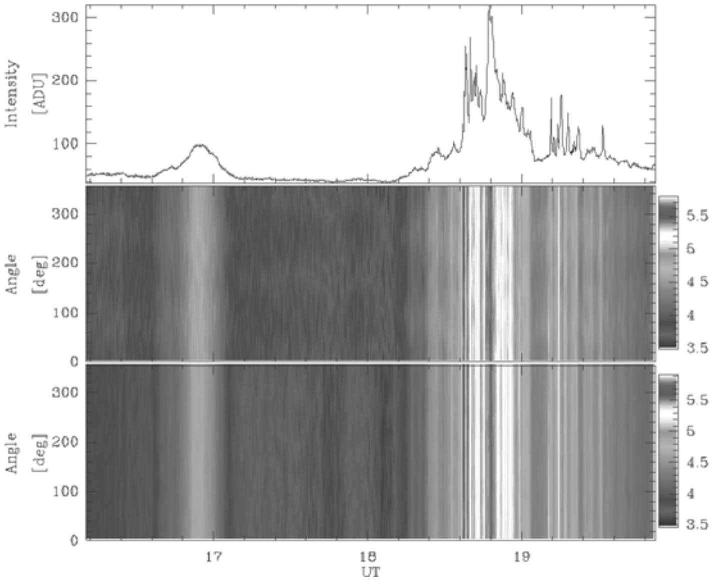

Figure 1. (top) Total intensity integrated over each 4.02-second cycle as a function of universal time. (middle) Logarithm of channel 1 data versus the angle of the polarization lens. (bottom) Logarithm of channel 2 data.

relatively constant at −15°C and the sky remained clear. We performed measurements pointing towards magnetic North with an elevation of 15°. At the altitude of 220 km, the angle between the line of sight and the Earth magnetic field is 83°, the crossing point being located above the North-East shore of Greenland. A complete description of the data will be published later. The present paper focuses on January 17, which is representative of the other days.

[8] After dark current correction, we perform a Fourier analysis and apply a low-pass filter at 1.5 Hz. After filtering, we fit each measurement cycle with a sine squared function. The polarization parameters are extracted from this fit. These parameters are the amplitude (defined as the difference $Q = I_{\max} - I_{\min}$ between the maximum and the minimum intensities), the degree (P = $\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$) and the direction of the polarization. If polarization is present, the signal should exhibit two maxima during a cycle, i.e. a 0.5 Hz signal, exclusively in channel 1.

[9] We examined possible artefacts. The aperture (2°) and the stability of the polarization over several hours exclude a star effect. Absence of instrumental induced polarization was checked in laboratory. We do not use any dome above the instrument. To insure thermal equilibrium of the photomultipliers, we consider only data recorded after more than 8 hours of acquisition and in stable meteorological conditions with temperatures below about −15°C.

[10] We examined the effects of parasitic sources that could affect the signal: airport, city light scattered on the snow or on aerosols including smoke emanating from the heating power plant [*Garstang*, 1986; *Cinzano*, 2000; *Cinzano et al.*, 2000; *Kocifaj*, 2007]. We eliminated the city light artefact by considering the polarization direction: it has tendency to induce polarization with constant direction. We also envisioned the parasitic polarization of the light through Mie scattering by atmospheric water droplets. The atmosphere remained dry before and during the experiment. We ruled out Rayleigh multiple scattering of solar light in the lower atmosphere (below 50 km) which could

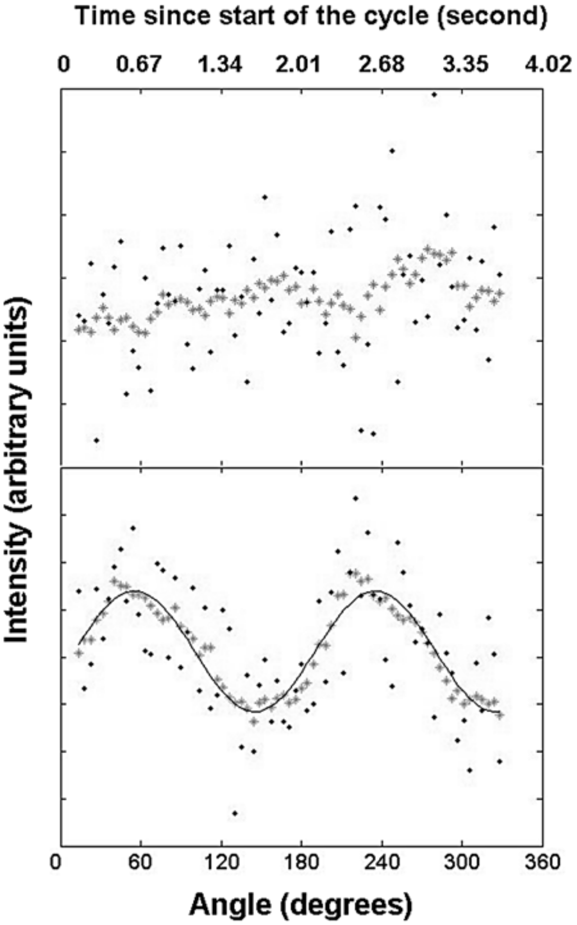

Figure 2. (top) Non polarized and (bottom) polarized channel data averaged over 50 cycles around 18:50 UT, when the emission intensity is at maximum. The points and the crosses correspond to the measurements and to the filtered data, respectively, and the line is the fitted sine squared function.

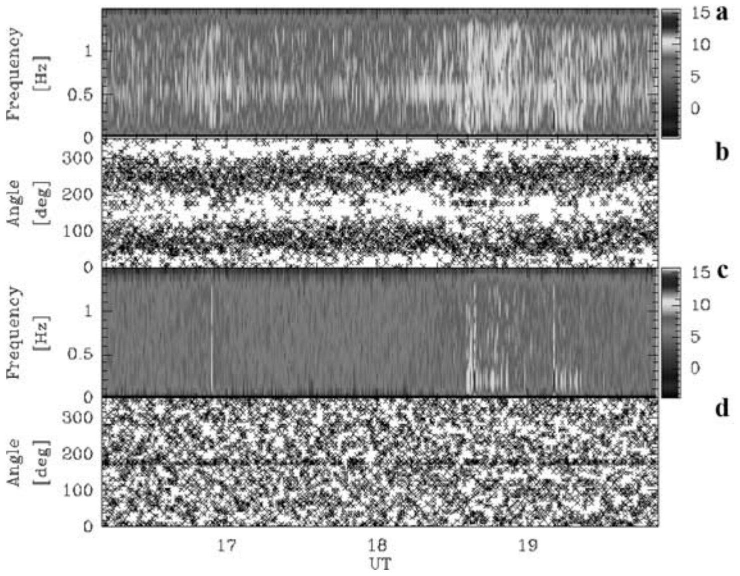

Figure 3. Fourier transform analysis of the (a) and (b) polarized and (c) and (d) non polarized channel as a function of universal time. The 3D plots show the power spectrum densities. The 2D plots show the positions of the maxima of the fitted squared sine functions. The measurements are made exactly at the same times for both channels. Therefore, the angles in the y-axis correspond to the rotation of the lens in the polarized channel. In both channels, the intense features between 18:30 and 19:30 at low frequency are due to rapid variations of the total intensity during auroral events.

create polarization [*Ugolnikova et al.*, 2004; *Cronin et al.*, 2006] for solar zenith angles smaller than 108°. However, there is still one artefact that we have not been able to rule out: the scattering of the emission of the aurora itself from low altitude atmospheric layers.

3. Results

[11] We focus on a succession of auroral events between 16 UT and 20 UT. These events are very intense (the total flux is increased by a maximum factor of 80). The signal is plotted versus the polarisation filter angle and versus time in Figure 1. Figure 2 shows an example of the polarized and non polarized data averaged on 50 cycles versus the angle. The analysis shows the expected 0.5 Hz signal almost all along the experiment and only in channel 1 (Figure 3). The amplitude Q and the degree of polarization P clearly vary with the upper total auroral intensity (Figure 4). P and Q are quite constant at the beginning of the dataset. Q has a mean value of about 3 (in arbitrary units a.u.) and increases during the auroral events up to about 10 a.u. The P value averaged over 15 cycles varies between 2% and 6% with single cycle values beyond 10%. As a matter of comparison, values of less than 2.5% are considered to be significant in solar observations [*Henoux et al.*, 1990]. However, these values must be considered with care, as they may not be the exact values of the polarization degree in the aurora: it cannot be excluded that some parasitic light contributes, increasing or decreasing P.

[12] In absence of auroral event, the polarization direction (computed on a one minute or 15 cycle integration) remains particularly stable. This may be seen in Figure 3b on the maxima of the signal or in Figure 4 (bottom) on the polarization direction. The values are of 75° (0° being the vertical axis oriented towards the ground). The variability in term of mean square root is 3.5°. During the first aurora (shortly before 17 UT), the polarization direction varies down to 58° with a larger variability of 5°. During the second aurora (between about 18:30 UT and 19:35 UT), the polarization direction goes down to about the same angle (66°) with a variability of 7°. The variability of the direction reflects the dynamics of the aurora. The evolution of the correlation between the phase and the intensity of the aurora is a clear indication that the phase variation can only be attributed to the aurora (from 16 to 20 UT, the correlation coefficient is −0.3 while it increases to −0.5 during the

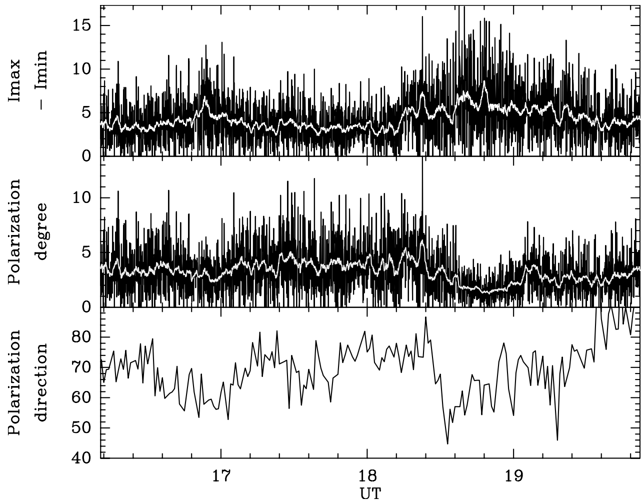

Figure 4. (top) Amplitude Q of the polarization (arbitrary units) as a function of universal time. (middle) Polarization degree P. The white lines are running averages over 15 cycles. (bottom) Polarization direction (0° being vertical). Because of the low SNR the cycle per cycle value is not computed as for P or Q.

auroras). However, this effect can still be attributed to the scattering of the emission of the aurora from low altitude atmospheric layers.[1]

4. Discussion

[13] The anti-correlation between P and Q supports the following picture: the polar rain is permanent. It precipitates electrons at about 500 eV at the top of the atmosphere and results in a permanent polarization in the red line emission. During an auroral event, the electrons flux at 500 eV is enhanced as is the amplitude Q of the polarization. But there is also additional high-energy electron precipitation. If the latter create less polarization, the ratio P will decrease while Q increases.

[14] These characteristics strongly differ from Duncan's historical attempt in 1958 [*Duncan*, 1959]. We observe an almost permanent polarization in the polar cap. At middle geomagnetic latitude (42°S) and with a magnetic inclination of about 30°, Duncan observed a polarization only on July 9th; 1957 out of 31 nights with a 30% polarization degree surprisingly too high, whereas our measured 2% value during an intense event is more compatible with Chamberlain's considerations.

[15] When confirmed, this discovery will have major impacts. Let us mention three of them. The first is theoretical. This oxygen line polarization has never been studied in the past because the theory of the polarization of a forbidden transition by electron impact is not understood. The only attempt [*Kazantsev et al.*, 1999] neglects several aspects, in particular the relativistic effects which are important during the collision [*Štepán et al.*, 2007; *Sahal-Bréchot et al.*, 1996]. Our measurement raises new insights to help solving this question.

[16] The second one deals with geophysics, and particularly space weather and terrestrial aeronomy. Polarization properties are already used in comets [*Hadamcik et al.*, 2006], planetary mesospheres [*Rodin et al.*, 1997], or Earth magnetosphere [*Hanasz et al.*, 2006] studies but have never been used for thermospheric or ionospheric purposes. In these atmospheric layers, the total electron content and the oxygen green line intensity vary with the geomagnetic activity [*Culot et al.*, 2005], but not the intensity of the red line. The two former parameters are not enough to constrain thermospheric models [*Lilensten and Blelly*, 2002]. Since the polarization seems to be mostly due to low-energy electrons and its degree decreases when the activity increases, it shows up as an innovative way to monitor the upper atmosphere variations. This of course will require an important statistical study.

[17] Finally, this discovery will provide the community with an additional means to access magnetic and dynamic ionospheric parameters at the same time in planetary upper atmospheres. As many radiative transitions of atmospheric gases are likely to be polarized [*Lilensten et al.*, 2006], such measurements should be systematically envisioned on ground-based and space planetary atmospheric observations. Atomic oxygen itself is present in the upper atmospheres of Venus and Mars. The crustal magnetic field (on Mars) and the interplanetary magnetic field (on Venus and on Mars) can be considered as sources of anisotropy. The measurement of the direction of polarization will then become an original measurement of the magnetic field lines orientations. It will help understanding how the solar wind wraps the unmagnetized bodies and piles up [*Lundin et al.*, 2004; *Vennerstrom et al.*, 2003] in their upper atmospheres.

[18] Further experiments will be conducted in the near future in the same wavelength as well as in other emission lines. Finally, an experiment conducted from balloon or space could solve the remaining ambiguity between direct light of the aurora and light of the aurora possibly scattered from low altitude atmospheric layers.

[19] **Acknowledgments.** This work is dedicated to B. Duncan (1929 – 2004), who pioneered the field. The instrument has been mostly funded by the University of Oslo. We thank particularly Espen Trondsen, Lars Lyngdal, and Bjørn Lybekk. We have largely benefited from the help of the UNIS staff in Svalbard. This work has received funds from the French PAI Aurora, the French Solar_Terrestrial physics group (PNST), the Norwegian Research Council (Aurora), and AFOSR task 2311AS. It has been supported by the European COST 724 action and it is one of the International Heliophysical Year Coordinated Investigation Programmes. We thank Njål Gulbrandsen (UiO, Oslo, Norway), Y. Ogawa (NIPR, Japan), Béatrice Pibaret (LPG, France), and Yannis Hurtaud (CESR, France) for their help during the campaigns. We thank Sylvie Zanier (UJF, France) for access to lens testing facility and Sylvie Sahal-Bréchot and Véronique Bommier for essential inputs on the physics of the polarization.

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