"Physics of Auroral Phenomena", Proc. XLVI Annual Seminar, Apatity, pp. 61-64, 2023

Polar Geophysical Institute

DOI: 10.51981/2588-0039.2023.46.013

AURORAL OVAL LONG-TERM CHANGES LINKED TO SECULAR VARIATIONS IN EARTH'S MAGNETIC FIELD AND GEOMAGNETIC ACTIVITY

Jose A. Ochoa[1], Bruno S. Zossi[1,2] and Ana G. Elias[1,2]

[1]*Laboratorio de Ionosfera, Atmosfera Neutra y Magnetosfera (LIANM), Departamento de Física, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucumán, Argentina*
[2]*INFINOA, CONICET-UNT*

Abstract

Changes in the Earth's magnetic field and in geomagnetic activity through solar wind conditions can both deeply modify the auroral ovals, which are the regions of most frequent precipitation of energetic particles causing aurora. These two auroral change drivers present long-term trends: the well-known magnetic field secular variation, and the Gleissberg cycle of solar and geomagnetic activity that can also be considered as a secular variation. In this work, both induced long-term changes are compared by estimating the variations in the auroral zone boundaries and area as a consequence of each one acting independently during the period 1932-2022. That is the last 9 decades, which is the period covered by Kp geomagnetic activity index availability. In the first case, the IGRF is used to estimate the time-evolution of the zone enclosed by the fixed geomagnetic latitudes typical for auroral boundaries during quiet geomagnetic activity levels considering steady interplanetary conditions and assuming scaling relations for a purely dipolar field. In the second case, under fixed Earth's magnetic field conditions, a Kp-based model is used considering an 11-year running mean of this index in order to filter out short-term variations typical of geomagnetic activity. A comparative analysis is then made between the auroral ovals modifications over these last 9 decades.

1. Introduction

The auroral ovals are regions where charged particles accelerate along magnetic field lines from the magnetosphere to the upper atmosphere. They play an important role in space weather (*Akasofu*, 1983; *Feldstein*, 2016) due to the consequences of particle precipitation on technological systems which during certain solar events, such as geomagnetic disturbances, can disrupt terrestrial communications, geospatial positioning systems, and satellite equipment, among other effects (*Olson and Amit*, 2006; *Hayakawa et al.*, 2020).

The auroral oval's nearly circular boundary, whose center aligns with the eccentric geomagnetic dipole (*Tsyganenko*, 2019; *Zossi et al.*, 2020) is linked to Earth's magnetosphere, which, in turn, depends on the geomagnetic field and solar wind conditions. They both present long-term changes that can lead to variations in auroral oval position, areas, and auroral frequency (*Silverman*, 1992).

Over the past 180 years, the secular variation of the geomagnetic field has been marked by a rapid dipole moment decrease (*Olson and Amit*, 2006; *Huguet et al.*, 2018). Under the self-similarity hypothesis for a pure dipole magnetic field and a steady solar wind during quiet conditions, and based on scaling relations, the polar cap boundary will shift to lower latitudes with a consequent increase in polar cap area as the Earth's dipole moment becomes weaker (*Siscoe and Chen*, 1975; *Vogt and Glassmeier*, 2001; *Glassmeier et al.*, 2004). Since the inner auroral ovals' boundary is given by the polar cap, then this shift to lower latitudes and area increase are also expected in auroral ovals' case. (*Schulz*, 1997; *Zossi et al.*, 2020).

Solar and geomagnetic activities exhibit long-term changes of longer timescales than the well-known quasi-decadal solar activity cycle, such as the ~90-year Gleissberg cycle (*Feynman and Ruzmaikin*, 2014), that also have an impact on auroral ovals. There are analytical models that simulate the auroral oval boundaries in terms of geomagnetic activity indices, such as Kp. For example, the methods by *Starkov* (1994) and *Zhang and Paxton* (2008). Through these methods, it is possible to assess the consequences of geomagnetic activity long-term variation on auroral ovals considering the long-term component of Kp variability. It can be anticipated that an increase in Kp, will lead to a shift of the oval towards lower latitudes and an expansion in its area, that is trends of the same sign as those resulting from a decrease in the geomagnetic field, while a decrease would produce the opposite effect.

In the present work, a comparison is made between the auroral ovals modifications along the last 9 decades due to both long-term trend drivers: Earth's magnetic field secular variation, considering the scaling law, and the long-term changes of the geomagnetic activity considering Starkov's method.

2. Methodology

In order to assess the effect of the geomagnetic activity's long-term changes on the auroral ovals, the empirical formula to determine auroral oval's boundaries in terms of Kp given by *Starkov* (1994) was used:

$$\theta = A_0 + A_1 \cos[15(t + \alpha_1)] + A_2 \cos[15(2t + \alpha_2)] + A_3 \cos[15(3t + \alpha_3)], \tag{1}$$

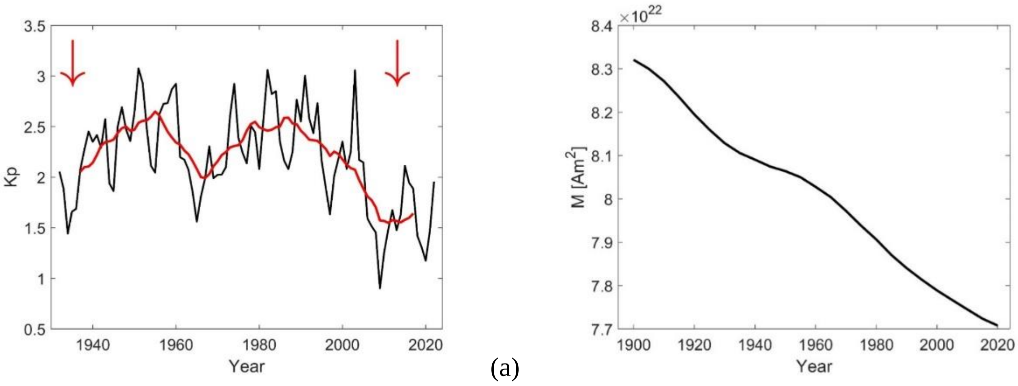
where θ is the boundary colatitude in geomagnetic coordinates and t is the local time in hours. The amplitudes A_i and phases α_i are obtained from

$$A_i \; or \; \alpha_i = a_0 + a_1 \, log_{10}(AL) + a_2 \, {log_{10}}^2(AL) + a_3 \, {log_{10}}^3(AL) \,, \tag{2}$$

where a_i are constants tabulated for the outer (equatorial) and inner (polar) boundaries of the auroral oval and AL is calculated with Kp from

$$AL = 18.0 - 12.3 \, Kp + 27.2 \, Kp^2 - 2.0 \, Kp^3 \,. \tag{3}$$

In order to consider the long-term variation of Kp (obtained from https://kp.gfz-potsdam.de/app/files/Kp_ap_since_1932.txt), the original time series was smoothed with an 11-year running mean, shown in Fig. 1a. Fig. 2, shows as an example the auroral ovals obtained from Starkov model for a 11-year smoothed Kp value for 1937, that is Kp = 2.05.



(a) (b)

Figure 1. (a) Kp index annual mean (black) and 11-year running mean (red). Red arrows indicate minimum periods of the Gleissberg cycle. (b) Secular variation of the dipole moment, M, of the Earth's magnetic field, obtained from IGRF-13.

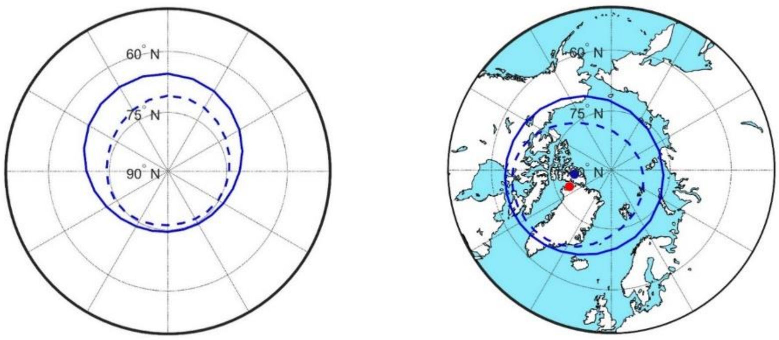


Figure 2. Auroral oval equatorward (solid blue) and poleward (dashed blue) boundaries in (left panel) geomagnetic coordinates, with 12 LT at 0° (this is the sunward direction and where the auroral oval is thinner), and in (right panel) geographic coordinates in the northern hemisphere (sunward direction is along ~70°W, which is the angle rotated by the Centered Dipole Coordinates with respect to the geographic coordinates). The red and blue dots indicate the position of the north Centered Dipole geomagnetic and Eccentric Dipole geomagnetic poles, respectively.

To estimate the effect of Earth's magnetic field variation on the auroral ovals position and area, we begin considering the scaling relation of the polar cap boundary, λ_p (that is the poleward boundary of the auroral oval), in terms of the Earth's dipole moment, M, given by:

$$cos(\lambda_p) \propto M^{-1/6} p^{1/2} \tag{4}$$

p being the solar wind dynamic pressure. This is valid assuming self-similarity for any value of M and p, which is indeed fulfilled by a pure dipolar field. We assumed that both, the equatorward and poleward auroral boundaries have the same scaling relation and that p remains constant. The initial boundary conditions are derived from the Starkov analytical model considering the first Kp value of the 11-year running mean time series.

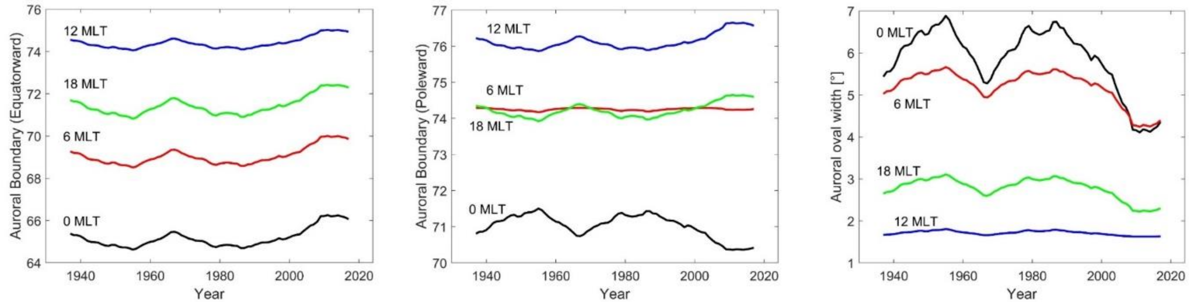
The secular variation of M is obtained from

$$M = 4\pi {R_T}^3 \sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}\,, \tag{5}$$

where R_T is the Earth radius (6371 km), and g_1^0, g_1^1 and h_1^1 are the Gauss coefficients obtained from the IGRF-2013 model (*Alken et al.*, 2021). Fig. 1b shows the secular variation of M from 1900 to 2020.

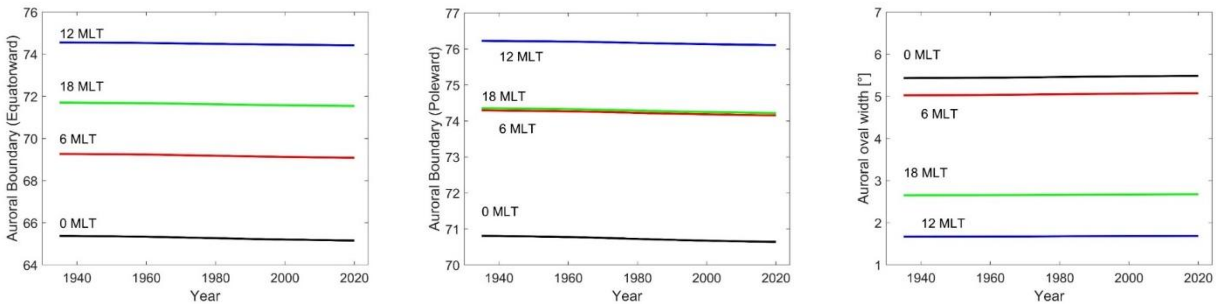
3. Results

Fig. 3 presents the long-term variation of the geomagnetic latitude position at 0, 6, 12, and 18 MLT, of the equatorial and polar boundaries due to Kp long-term variation, with Earth's magnetic field fixed in 1937. The auroral width, obtained as the difference between the polar and equatorial boundaries is also shown. Fig. 4 shows the corresponding long-term variations but due to the Earth's magnetic field secular variation keeping Kp fixed, and initial boundaries being those given by Starkov model for this year.



(a) (b) (c)

Figure 3. Time variation of the auroral oval (a) equatorial and (b) polar boundaries, and (c) latitudinal width, obtained with Starkov model and considering Kp 11-year running mean time series, at 0 (black), 6 (red), 12 (blue), and 18 (green) MLT. Earth's magnetic field fixed in 1937.



(a) (b) (c)

Figure 4. As in Figure 3 but obtained with scaling laws varying the Earth's magnetic field and keeping Kp fixed in 1937, and the initial boundaries from Starkov model in this year.

Fig. 5 presents the long-term variation of the geomagnetic auroral oval area due to geomagnetic activity and to the Earth's magnetic field secular changes in km^2 and also in percentage, from where it can be clearly noticed the difference in the overall effect of each trend driver along the period considered.

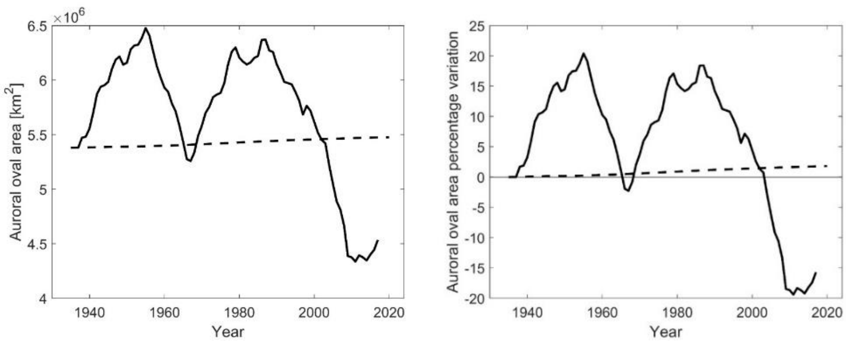


Figure 5. Time variation of the auroral oval area due to geomagnetic activity (solid line) and Earth's magnetic field (dashed line) variations in (a) km^2 and (b) percent with respect to the whole auroral oval area for the given year.

4. Discussion and conclusion

As can be noticed from the figures above, the Gleissberg cycle along the period considered consists of crests and troughs, against the almost linear trend of the Earth´s magnetic field dipolar intensity. This is evinced by the auroral oval long-term variation considering the Starkov model and scaling law to determine each driver effect in Figs. 3, 4 and 5. However, Kp presents also an overall almost linear decrease along the whole period, superposed to the Gleissberg variation, whose effects could be compared to the decrease in the Earth's field. Table 1 presents the resulting auroral boundary trends from where it can be concluded that the long-term geomagnetic activity decrease produces a poleward shift of the auroral ovals, against the equatorward shift expected from the magnetic field decrease. However, the trend due to Kp is an order of magnitude greater than that due to the Earth's field.

Table 1. Linear trends of the auroral oval equatorward and polar boundaries, for different MLTs, due to the overall linear trend in Kp and in the Earth's magnetic field dipolar intensity.

MLT	Equatorward boundary [°/year]		Poleward boundary [°/year]	
	Kp variation	Magnetic filed variation	Kp variation	Magnetic filed variation
0	0.0113	–0.0028	–0.0077	–0.0028
6	0.0102	–0.0024	0.0001	–0.0024
12	0.0066	–0.0017	0.0056	–0.0017
18	0.0108	–0.0021	0.0047	–0.0021

These trends in the auroral oval area result: –14719 km^2/year (–0.26 %/year) due to Kp long-term trend variation, and 1248 km^2/year (0.02 %/year) due to Earth's magnetic field secular variation. They are opposite but do not cancel.

The long-term variation linked to geomagnetic activity long-term variation linked to the Gleissberg cycle is stronger but cyclical. In 1000 years it could be null. The long-term variation linked to the Earth's magnetic field secular variation linked to the dipolar component only is much weaker, but steady. In 1000 years will be stronger.

Acknowledgments. Argentina's Consejo Interuniversitario Nacional provided financial support to J.A. Ochoa through the research fellowship Beca-EVC-CIN.

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