A Model of the Auroral Electrojet Dynamics Based on Planetary K-Index

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Abstract

The solar wind-magnetosphere coupling and the magnetosphere-ionosphere coupling form a current system, also known as an electrojet. The current system formed in the auroral regions during the main phase of geomagnetic storms is a phenomenon called auroral electrojet. In this research, the number density, temperature, and velocity of the auroral electrojet electrons were calculated theoretically by relating them to the Planetary K-index, a measure of the disturbance in the Earth's magnetic field.

1 Introduction

The solar wind, an electrically charged magnetized plasma emitted from the sun at supersonic speed, interacts in a complex way with the Earth's magnetosphere-ionosphere system [1, 2]. Auroral electrojet is a phenomenon that occurs at the altitudes of the E region of the Earth's ionosphere in the auroral regions, with the energy transferred from the solar wind plasma spreading and dissipating in the ionosphere [3, 4]. Ionospheric disturbances caused by auroral electrojet activities are an important factor in space weather forecasting and research due to their effects on both radio communications and satellites.

Gallagher et al. stated that the plasma pressure gradient formed in the magnetosphere creates gradient-curvature drift currents defined as Birkeland currents, which are currents entering and leaving the ionosphere by following the magnetic field lines. Currents that close this Birkeland current circuit and flow horizontally across the ionosphere are auroral electrojet currents [5]. Auroral electrojets, which vary according to the solar cycle and solar wind conditions, are known as ionospheric currents, which are the most difficult to identify and predict [6]. It was stated by Kamide and Vickrey that the electrojets flowing in the conductivity channels developed at high latitudes vary according to the local time [7].

Kamide and Brekke found that the high latitude electrojet altitude to the east was approximately 120 km [8]. However, they stated that the average altitude of the electrojet towards the west is about 100 km, but it also changes over time. Sato et al., on the other hand, found that the height of the electrojets formed towards the east and west was similar to the values of Kamide and Breke [9]. Sato et al. also stated that the altitude of the electrojet may occur depending on the phase of the electrojet. This current's closure height is considered an important parameter for Magnetosphere-Ionosphere coupling. The importance of understanding auroral electrojets for space exploration was discussed by Smith et al. [6].

In this study, it is aimed to keep as little experimental data as possible, depending on the number density profiles, temperature profiles, and velocities of auroral electrojet electrons in the Earth's ionosphere, and planetary K-index. Thus, the accuracy in predicting the electron dynamics of the auroral electrojet can be increased.

2 Auroral Electrojet Density Profile

The auroral luminosity, and thus the electron density in the auroral electrojet behaves as α-Chapman distribution, ergo the electron density n_e^{ae} profile as a function of altitude could be written [10, 11, 12],

$$n_e^{au}(h) = 10^6 e^{\frac{1}{2}\left(1-z^{au}-e^{-z^{au}}\right)}. \qquad (1)$$

Where $z^{au} = \frac{h-h_{max}^{au}}{H^{au}}$, $h_{max}^{au} \sim 115\ km$ is the peak electron density height of the auroral electrojet and $H^{au} = \frac{kT^{au}}{mg}$ is the scale height, where k is Boltzmann constant, m is mass of particle, and g is the gravity acceleration.

3 Temperature of the Auroral Electrojet

Wickwar estimated the temperature of ions as a function of ion velocity based on Schunk's calculations under steady conditions where neutral particles are stationary [13, and references in]. Assuming $T_e \approx T_i$ gives the temperature of the auroral electrojet electrons,

$$T_e^{ae} = 9 \times 10^{-4} \vec{u}_e^{\,2} + T_n. \qquad (2)$$

Where $\vec{u}_e$ is the electron velocity and T_n is the neutral temperature. To find the T_n above 100 km, the Bates profile could be used, in which allows to calculate the neutral temperature in terms of altitude h, exospheric temperature T_∞ , T_n at altitude 120 km, T_{120} , $z = (h - 120\ \text{km}) \frac{R_E + 120\ km}{R_E + h}$, which is the geopotential height above the 120 km base used where R_E is the radius of the Earth, and the shape parameter s, [14, and references in]

$$T_n(h) = T_\infty - (T_\infty - T_{120})e^{-sz}. \tag{3}$$

Later, Oliver et al., suggested the relation between s and T_∞ as $\frac{16,80}{T_\infty}$ [13] and $T_{120} = 355\ \mathrm{K}$ [15]. For simplicity, T_∞ could be estimated via the addition of difference ΔT_∞ due to geomagnetic activity and the latitudinal variables to the globally averaged exospheric temperature $\bar{T}_\infty$,

$$T_\infty = \bar{T}_\infty + \Delta T_\infty. \tag{4}$$

Where $\bar{T}_\infty \approx 1{,}155.T_{\infty\,\mathrm{min}}$ [16], and $T_{\infty\,\mathrm{min}}$, the global nighttime minimum exospheric temperature equal [17],

$$T_{\infty\,\mathrm{min}} = 4{,}47.\mathrm{S} + 275. \tag{5}$$

Where S is the monthly average of the F10.7-cm flux. Also, ΔT_∞ taken from the Jacchia's hybrid formula [18],

$$\Delta T_\infty = 14°\mathrm{Kp} + 0{,}02.e^{\mathrm{Kp}}. \tag{6}$$

In the light of all these assumptions and equations, with decimals are rounded for ease of calculation, Equation (2) is rewritten as follows,

$$\begin{aligned} T_e^{ae} = {} & 318 + 5\mathrm{S} + 14\mathrm{Kp} + 9.10^{-4}{\vec{u}_e}^2 \\ & - (5\mathrm{S} + 14\mathrm{Kp} - 37)e^{-\frac{z}{19+2\mathrm{Kp}+0{,}3\mathrm{S}}}. \end{aligned} \tag{7}$$

The velocity required to find the temperature will be calculated in the next section.

4 Velocity of the Auroral Electrojet Particles

Nisbet et al. calculated the total Birkeland current entering the hemispheres using empirical statistical methods for winter I_{tw} and summer I_{ts} seasons as follows [19],

$$\begin{aligned} I_{tw} &= 5.10^5.e^{0{,}44Kp}, \\ I_{ts} &= 7{,}6.10^5.e^{0{,}43Kp}. \end{aligned} \tag{8}$$

By fitting these equations into a sinusoidal model, the following a new function can be obtained,

$$I_t = 10^5.e^{0{,}43Kp}\left(5.e^{0{,}01Kp}\sin\left(\frac{2\pi t}{T}\right) + 7{,}6\right). \tag{9}$$

Here T can be a seasonal, monthly, or daily period of t, with $t = 0$ summer. The current equation can be written depending on velocity and density, from $I = qnA\vec{u}$, where q is the charge of current which is e, and n is the number density of auroral electrojet, A is the cross-sectional area of the auroral electrojet current which is elliptic-shaped. Since the auroral electrojet flows in the same direction as the latitudes, then the A could be calculated by height, the difference between the equatorward θ_{Eq} and the poleward θ_{Po} auroral oval boundaries,

$$A = \frac{\pi R_E}{2}\left(h_m^{ae} - h_{min}^{ae}\right)\left(\theta_{Po} - \theta_{Eq}\right). \tag{10}$$

Where $R_E = 6371\ km$ is the radius of the Earth, $h_{max}^{ae} \sim 115\ km$, $h_{min}^{ae} \sim 90\ km$ is the minimum height of the auroral electrojet. $\theta_{Po} \sim 75°$ could be approximated constant for every local time (LT), and θ_{Eq} can calculated as [18],

$$\theta_{Eq} = 18° + 0{,}9\mathrm{Q} + \cos(\mathrm{LT} - 12°). \tag{11}$$

Where magnetic Q index equals a function of planetary Kp index, which introduced later [20],

$$\mathrm{Q} = 1{,}5\ \mathrm{Kp} - 1{,}7. \tag{12}$$

Assuming $n_e^{ae} \approx \rho_e$ where ρ_e is the number density of the electrons in the solar wind. Then, the velocity of auroral electrojet $\vec{u}_e$ could be written,

$$\vec{u}_e \cong \frac{1{,}3}{e\pi n_e^{ae}}\frac{e^{0{,}4Kp}\left(5\sin\left(\frac{2\pi t}{T}\right) + 7{,}6\right)}{\left(58{,}5° - 1{,}4\ \mathrm{Kp} - \cos(\mathrm{LT} - 12°)\right)}. \tag{13}$$

Where all components rounded to tenths. If Equation (13) is replaced in Equation (7) and it is replaced in Equation (1), both the temperature profile of the auroral electrojet electrons and the number density profile can be calculated with the least amount of experimental/observational data.

For the calculation of the Kp index in Equation (7) and (13), a new equation can also be written, which is calculated directly depending on the various solar wind parameters, if the following Newell's expression can be used, as the function of the solar wind ion density ρ, solar wind velocity v, magnitude of the solar wind magnetic field $B_t = \left({B_y}^2 + {B_z}^2\right)^{\frac{1}{2}}$ and magnitude of the interplanetary magnetic field (IMF) clock angle $\theta = \tan^{-1}\left(\frac{B_y}{B_z}\right)$, where lower cases are the direction of the magnetic field [21],

$$\begin{aligned} Kp = {} & 0{,}05 + 2{,}244.10^{-4}\left(\vec{v}^2 B_t \sin^4\left(\frac{\theta_c}{2}\right)\right)^{\frac{2}{3}} \\ & + 2{,}844.10^{-6}\sqrt{\rho}\vec{v}^2. \end{aligned} \tag{14}$$

Thus, all the values tried to be calculated throughout the study can be calculated for any desired region and at any time, with only the basic solar wind parameters and the F10.7 value.

6 Discussion

Since the number of parameters used is reduced to some solar wind parameters and F10.7, the polar region dynamics of the ionosphere and auroral electrojet dynamics, which have a highly dynamic structure with the help of magnetosphere-ionosphere coupling, with a closer approach to deterministic rather than the usual empirical approaches, theoretically. It has come a little closer to the situation that can be examined and predicted. However, the biggest shortcoming of the study is that the theory does not say anything in terms of 2 regions of the auroral electrojet called Region 1 and Region 2, and directional types such as westward and eastward, the authors are aware of this and are being studied. In future studies, this deficiency will be eliminated, the assumptions accepted for simplicity will be reduced, and the diffusion resulting from the obvious electron density difference between the auroral electrojet and the ionospheric E region will be examined in particular, and more numerical results will be revealed regarding aurora formation.

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