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A Comparison of Plasma Properties in the Ionosphere over Baghdad: The Daily and Seasonal during 2020-2022

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Abstract

This paper studies the effect of electron temperatures and densities on the F layer of the ionosphere during the seasons (winter, spring, summer, fall) of the first years of solar cycle 25 (2020-2022) in the sky of Baghdad, the capital (44.3° East, 33.3° North). The temperature and density data were taken from (IRI-2020) for the height (150-500) km with an increment of 50 km. The study shows that the values of electron temperature (T_e), Debye length λ_{De} , and the number of charged particles enclosed within a Debye shielding region $[(N)]_D$ in 2020 were higher than in 2022. Whereas the electron density (n_e) and plasma frequency (f_{pe}) in 2020 were lower than in 2022. It also shows that the plasma coupling parameter (Γ) was weak during both years. It was observed that the thermal velocity $[(v)]_{te}$ of the electron reached its highest Values for both years at an altitude of 500 km.

Keywords: Ionosphere, F Layer, Solar Cycle 25, Plasma properties, IRI – 2020 .

مقارنة خصائص البلازما في طبقة الأيونوسفير فوق بغداد: اليومية والموسمية خلال الفترة 2020-2022

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الخلاصة

في هذه الورقة البحثية، تم دراسة تأثير درجات حرارة الإلكترونات وكثافتها على خصائص البلازما لطبقة الأيونوسفير F خلال فصول السنة (الشتاء، الربيع، الصيف، الخريف) فوق العاصمة العراقية بغداد (44.3° شرقاً، 33.3° شمالاً) خلال عامي 2020 و 2022 التي تمثل بداية الدورة الشمسية 25 تم اخذ بيانات الحرارة والكثافة من (IRI-2020) للارتفاعات (150-500) كم بزيادة 50 كم. وتظهر الدراسة أن قيم درجة حرارة الإلكترون (T_e) وطول ديبي (λ_{De}) وعدد الجسيمات في كرة ديبي (N_D) في عام 2020 أعلى مما كانت عليه في عام 2022، في حين أن كثافة الإلكترون n_e وتردد البلازما f_{pe} في عام 2020 أقل مما كانت عليه في عام 2022. كما تثبت أن معامل اقتران البلازما (Γ) ضعيف خلال كلا العامين . وقد لوحظ أن السرعة الحرارية للإلكترون وصلت إلى أعلى مستوياتها لكلا العامين عند ارتفاع 500 كم

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1. Introduction

The atmosphere surrounds the Earth and acts as an effective protective shield by absorbing the harmful portion of solar radiation, thus protecting living organisms and ecosystems. The absorption of solar radiation within the atmosphere also results in the formation of electrons, ions, and neutral particles [1][2]. These processes contribute to the formation of the ionosphere. The ionosphere is located within the upper atmosphere, extending between altitudes of 50 and 800 km [3]. Figure 1 shows that the ionosphere is divided according to the electronic density into the D, E, F1, and F2 Layers. The F Layer has the highest electron density and is therefore the most important [4]. The study of the ionosphere is of great importance as it is the major cause of errors in communication systems, satellites, space weather, and positioning systems [5]. Plasma is the most abundant state in the universe, which makes up 99% of observable matter [6]. Plasma is a state of matter that is a nearly neutral ionized gas containing free electrons and ions along with occasional neutral particles, and is produced either by heating or by other ionizing means such as strong electric or electromagnetic fields and radiation [7]. In addition to the three known states of matter, plasma is a distinct fourth state [8]. In highly ionized plasmas, Coulomb forces control the interactions and behavior of particles, while in weakly ionized plasmas, interactions resulting from collisions with neutral particles dominate over those resulting between charged particles [9]. The Ionosphere is a layer containing natural plasma formed as a result of the interaction between the Atmosphere and the Sun [10]. The density of the Ionosphere changes according to solar activity, represented by sunspots and solar Flux [11], as well as the time during the seasons of the year and the day [12]. The relationship between the Ionosphere and plasma, which represents a vital area of scientific research that determines the total electron content associated with the twenty-third solar cycle, was calculated [13]. Several previous studies have examined the behavior of the heliosphere during solar cycles 23 and 24, indicating a link between the ionosphere and the number of sunspots [14] [15]. The purpose of the research is to calculate the plasma parameters at different heights of the ionosphere and to study the effect of sunspots and flux. In this research, the plasma properties of the ionosphere for solar cycle 25 were studied.

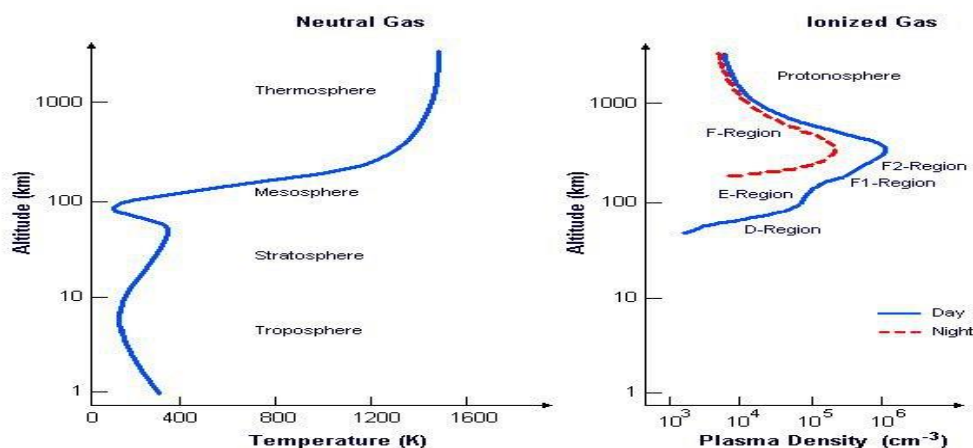


Figure 1: Differences in ionosphere layers during day and night [16].

Figure 1 shows that layers E and F of the ionosphere can be distinguished at night, while a new layer, D, appears during the day as a result of the ionization of the ionosphere by solar radiation, particularly X-rays and ultraviolet radiation. This layer lies below layer E, the uppermost layer of the ionosphere. Known as the F layer, it is divided into two regions, F1 and F2. This division is due to the influence of solar radiation, especially ultraviolet radiation.

Plasma parameter2

The properties of plasma are determined by several factors, the most important of which are the behavior of electrons in terms of temperature and density, in addition to the plasma frequency of electrons, the Debye length λ_{De} , and the number of particles within the Debye sphere [18][17]. These parameters determine the physical behavior of the plasma and its ability to conduct electricity. Studying these factors is essential for understanding the properties of plasma and its applications in space, advanced technologies, and nuclear energy.

2.1 Debye length

The Debye length is one of the most important parameters for plasma. Particles behave as an individual charge on a scale larger than (λ_{De}) , while they behave collectively when they are on a scale larger than (λ_{De}) [19]. The distribution of charged particles (ions and electrons) around a single charge and the formation of a cloud around the charge are described by Debye scattering[20]

$$\lambda_{De} = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}} = 69 \sqrt{\frac{T_e}{n_e}} \quad (1)$$

Where: n_e is the density of electrons in m^{-3} , T_e is the temperature in kelvin, Boltzmann constant is $(k_B = 1.38 \times 10^{-23} \text{ JK}^{-1})$, λ_{De} is the Debye length (m), e is the charge of an electron ($e = 1.602 \times 10^{-19} \text{ C}$), and ϵ_0 is the Vacuum permittivity ($\epsilon_0 = 8.85 \times 10^{-12} \text{ Fm}^{-1}$).

2.2 Plasma frequency of electron (ω_{pe}):

Plasma frequency: It is the frequency of the collective oscillatory movement of the electrons around the ions due to the exposure of the plasma to external disturbances [21]. The electrons are more responsive to the movement, while the ions are less due to their heavier weight [22].

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (2)$$

Where: m_e is the electron mass ($m_e = 9.11 \times 10^{-31} \text{ kg}$).

And the frequency is given by:

$$f_{pe} = \frac{\omega_{pe}}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \approx 8.98 * 10^3 \sqrt{n_e (cm^{-3})} \text{ Hz} \quad (3)$$

2.3 Number of particles in a Debye sphere (N_D): The more electrons in a Debye sphere, the greater its contribution to electrical shielding [23].

$$N_D = \frac{4\pi}{3} n_e \lambda_{De}^3 = 1.38 \times 10^6 \frac{T_e^{\frac{3}{2}}}{n_e^{\frac{1}{2}}} \quad (4)$$

2.4 The plasma coupling coefficient (Γ): The ratio of typical Coulomb potential energy to thermal energy [24].

$$\Gamma = \frac{1}{(4\pi \lambda_{De}^2 n_e^{2/3})} \quad (5)$$

2.5 Thermal velocity of electron (v_{te}): The speed of an electron's response to a change in the electric field [25]. It is one of the most important parameters because it determines many of the properties of the plasma [26].

$$v_{te} = \omega_{pe} \lambda_{De} \quad (6)$$

$$v_{te} = \sqrt{\frac{k_B T_e}{m_e}} \quad (7)$$

International Reference Ionosphere Model (IRI) 3

IRI is a project endorsed by the Committee on Space Research (COSPAR) and the Radio Research Institute (URSI). The IRI is an active component in the study of ionospheric parameters through analytical formulas based on fundamental data sets.[28].

It is used in many engineering and science applications and has undergone many verifications [29]. In this research, the IRI 2020 version was chosen to study the ionosphere.

4. Results and Discussions

In this research, the beginning of Solar Cycle 25 was chosen, which is represented by the years 2020 and 2022. Table 1 shows the smoothed sunspot numbers (SSN) and the smoothed solar radiative flux ($F_{10.7\text{cm}}$) [30].

Table 1: Monthly smoothed to the sunspot numbers (SSN) and the solar radiative flux ($F_{10.7\text{cm}}$) in the years 2020 and 2022 [30].

Month	SSN-2020	$F_{(10.7)} \text{ cm- 2020}$	SSN-2022	$F_{(10.7)} \text{ cm- 2022}$
Jan.	2.2	69.5	60.1	104.5
Feb.	2.7	69.8	64.7	108.4
Mar.	3.0	70.1	68.7	112.1
Apr.	3.6	70.5	73.0	115.9
May	5.6	71.6	77.4	119.2
Jun.	7.9	73.0	81.1	122.4
Jul.	9.0	73.8	86.7	127.3
Aug.	9.5	74.1	92.6	133.0
Sep.	10.5	74.5	96.5	137.4
Oct.	11.9	75.0	99.0	139.8
Nov.	13.6	75.5	101.2	141.4
Dec.	15.3	76.2	106.7	144.3

Figures 2 and 3 show the electron temperature(T_e)variations for the years 2020 and 2022, which represent the beginning of solar cycle 25, for altitudes of 150-500 km, with an increase of 50 km during daylight hours in four different seasons of the ionosphere F layer over the Iraqi capital, Baghdad, the increased temperature of electrons in the ionosphere was caused by increased ultraviolet and X-ray radiation from solar activity, leading to greater ionization and heating. This changed the density of the layers, affecting the reflection and propagation of radio waves and the quality of communications, using the IRI model in the study and the Microsoft Excel program.

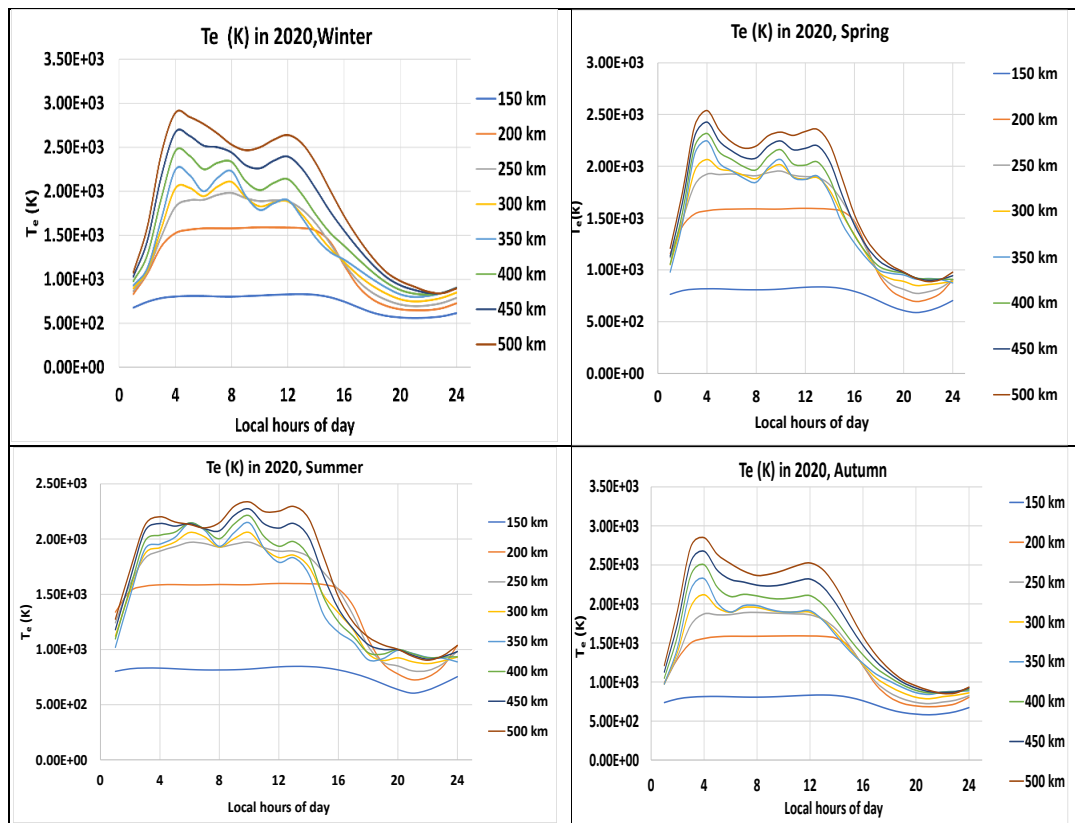


Figure 2: The electron temperature T_e at 12 pm for altitudes 150-500 km for the ionosphere F layer during the four seasons in 2020.

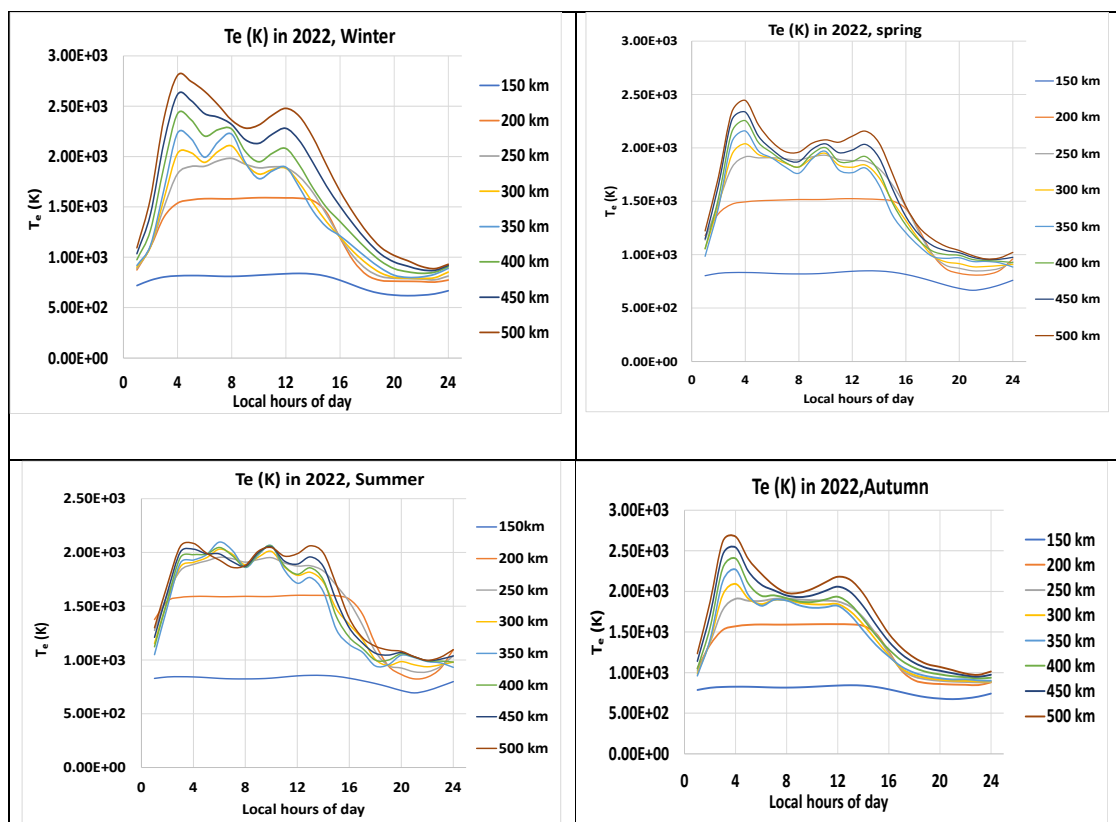


Figure 3: The electron temperature T_e at 12 pm for altitudes 150-500 km for the ionosphere F layer during the four seasons in 2022.

Figures 4 and 5 show the electron density (n_e) changes in the years 2020 and 2022, which represent the beginning of solar cycle 25, for altitudes of 150-500 km, with an increase of 50 km during the day's hours in four different seasons for the ionosphere layer F above the Iraqi capital, Baghdad, electron density was highest in spring and autumn due to the balance of solar radiation and solar wind during equinoxes, which increased ionization of the ionosphere, using the IRI model in the study and the Microsoft Excel program.

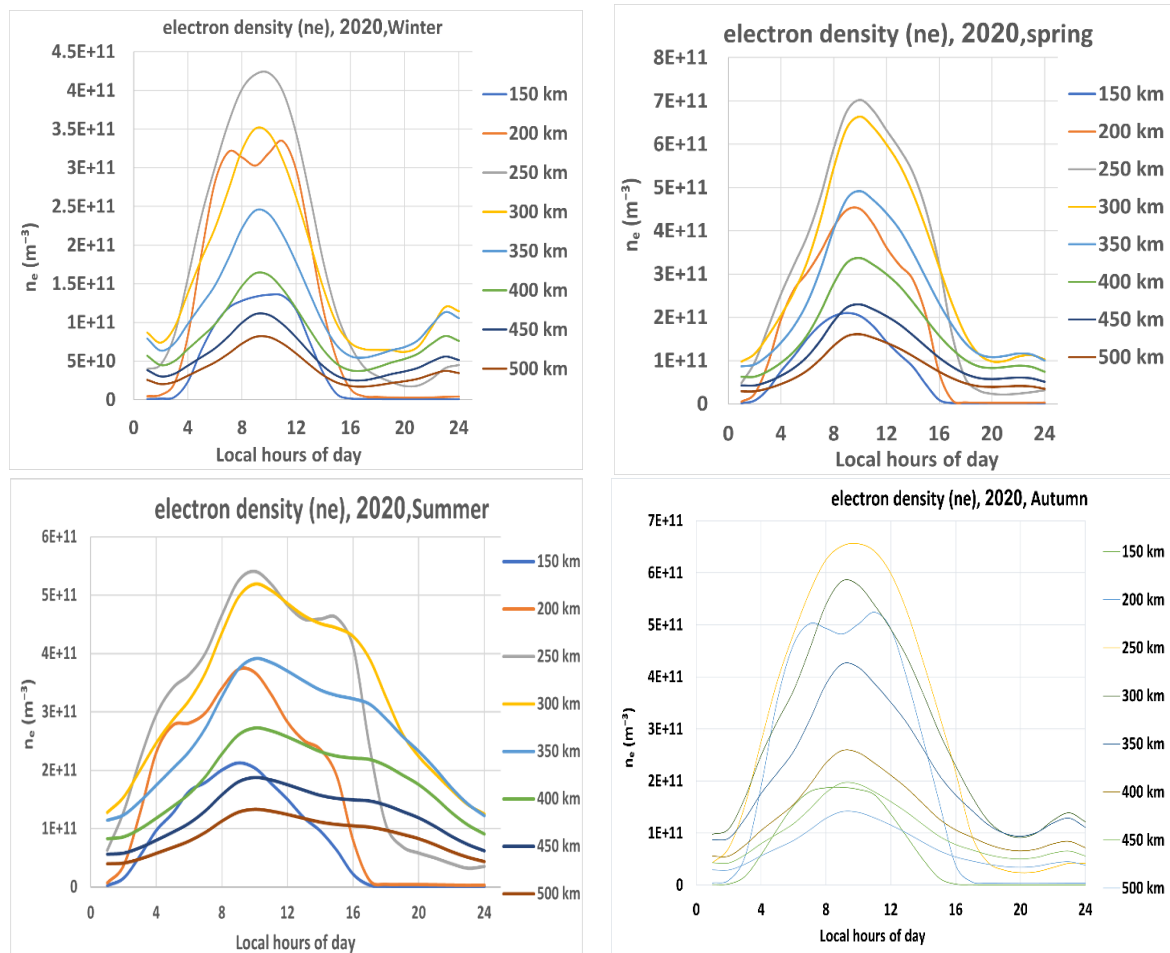


Figure 4: The electron density n_e at 12 pm for altitudes 150-500 km for the ionosphere F layer during the four seasons in 2020.

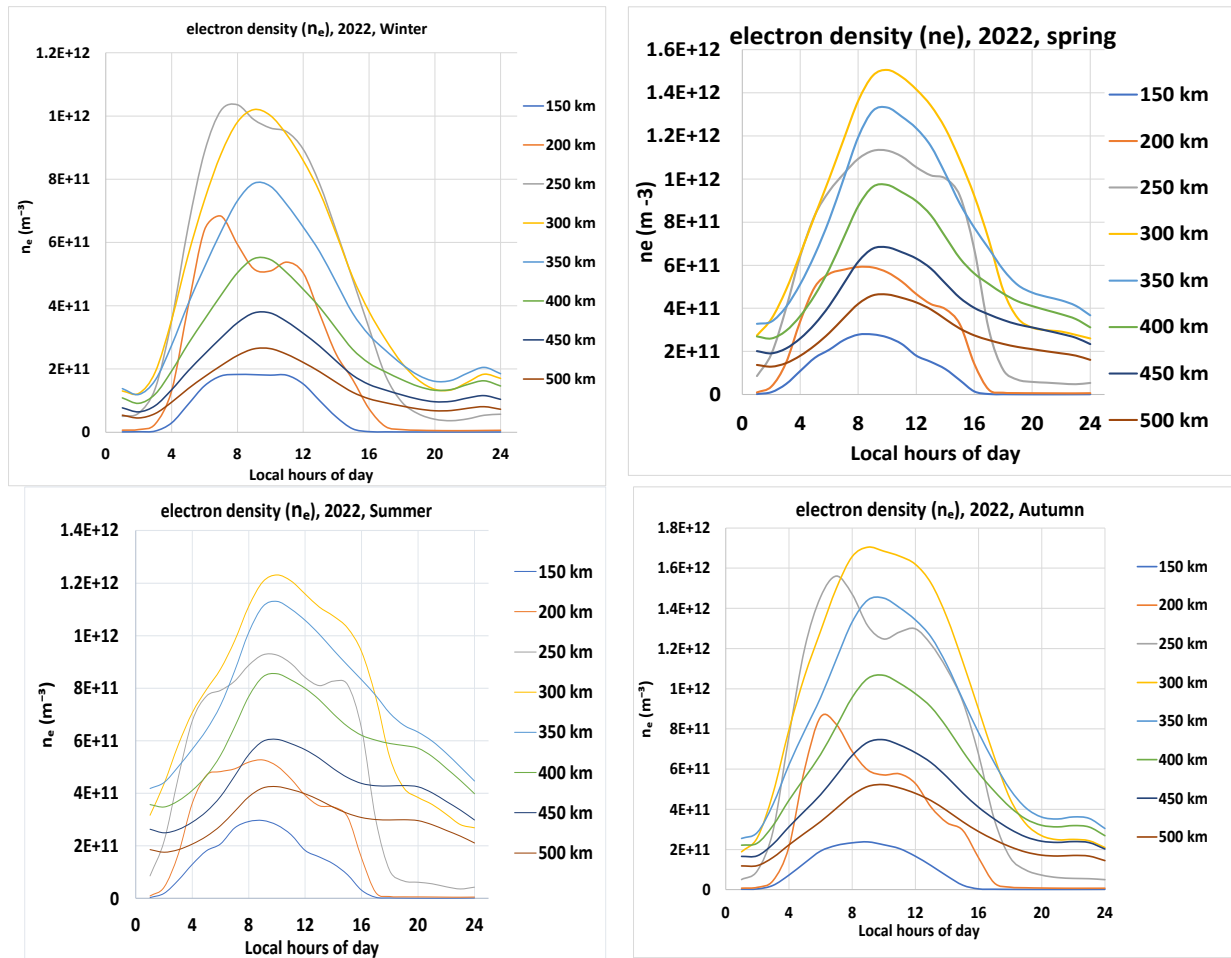


Figure 5: The electron density n_e at 12 pm for altitudes 150-500 km for the ionosphere F layer during the four seasons in 2022.

This work deals with the analysis of the plasma properties in the F layer of the ionosphere, at local time noon (12 pm), when ionization conditions are usually at their maximum, depending on the temperature and electron density for the years 2020 and 2022. The study showed an increase in the temperature and electron density during the day for altitudes 150-500 km, with an increase of 50 km. The work includes a study of the following plasma parameters (λ_{De} , f_{pe} , N_D , Γ , v_{te}) for each altitude.

Figure 6 shows the electron temperature during the years 2020 and 2022. The electron temperatures in both years were higher during the winter and spring seasons because the electron density decreased in winter and spring, collisions decreased, and the electrons heated up more, so their temperature rose.

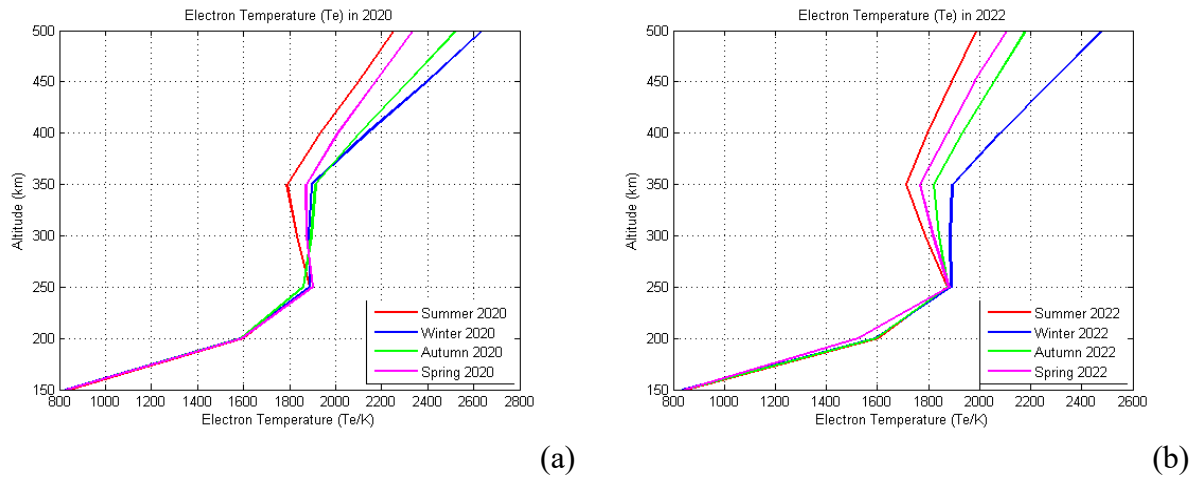


Figure 6: The electron temperatures T_e in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022. (a) The temperature of electrons in 2020, (b) The temperature of electrons in 2022.

Figure 7 shows the electron density (n_e) during the years 2020 and 2022. The electron density (n_e) in 2022 was higher than in 2020, reaching its highest value in spring and autumn at an altitude of 300 km.

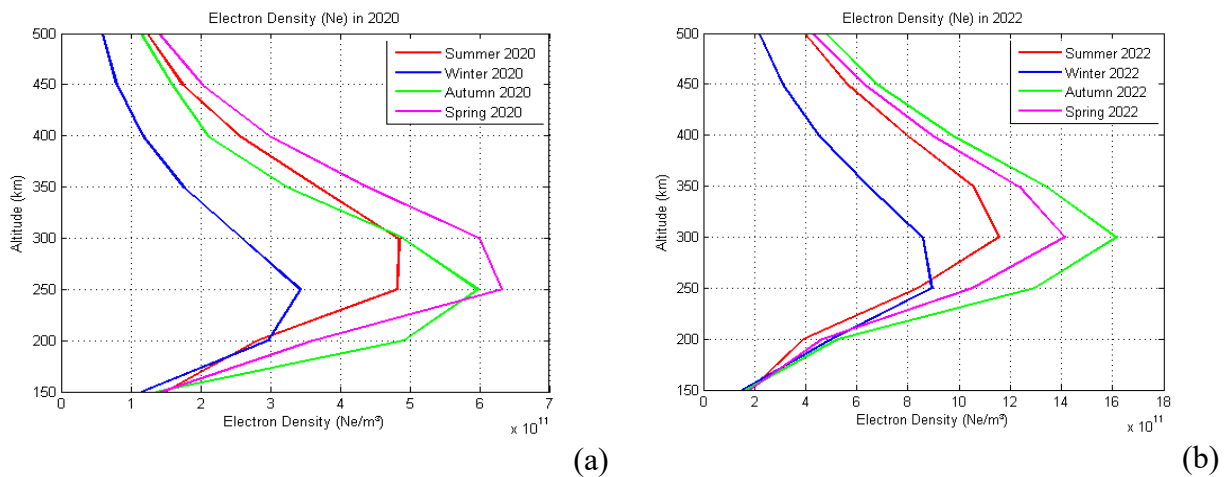


Figure 7: The electron density n_e in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022 (a) The electron density n_e in 2020 (b) The electron density n_e in 2022.

Figure 8 shows the Debye length (λ_{De}) during the years 2020 and 2022. The figure shows a decrease in the Debye length (λ_{De}) values from an altitude of 200 km to 250 km. At an altitude of 250 km, it begins with a slight increase until 300 km, after which it increases significantly to reach its peak at 500 km. The decrease was in winter during the years 2020 and 2022.

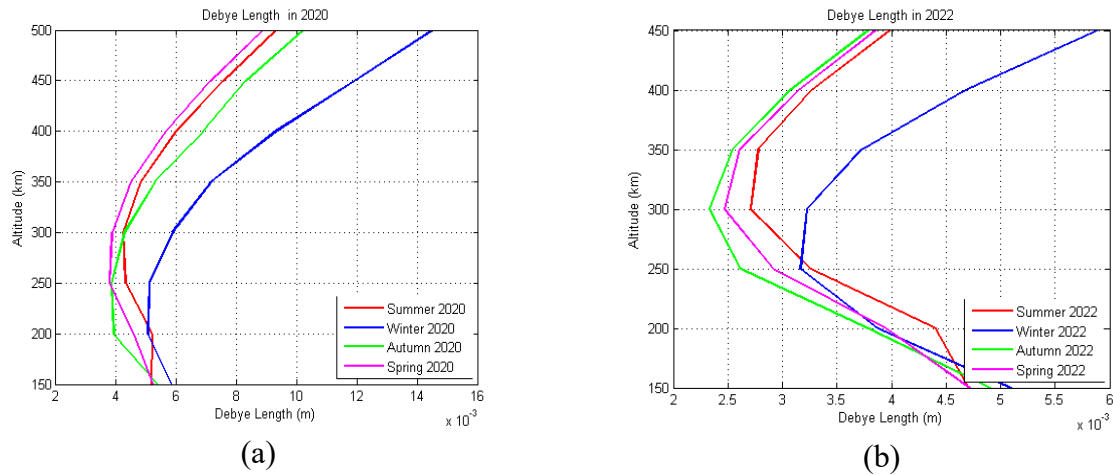


Figure 8: The Debye length λ_{De} in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022 (a) The Debye length λ_{De} in 2020, (b) The Debye length λ_{De} in 2022.

Figure 9 shows the Plasma frequency f_{pe} during the years 2020 and 2022. Plasma frequency values start to increase from 150 km to reach their peak at 300 km and then decrease to 500 km. Plasma frequency was higher during the transitional seasons than during the peak seasons of the year.

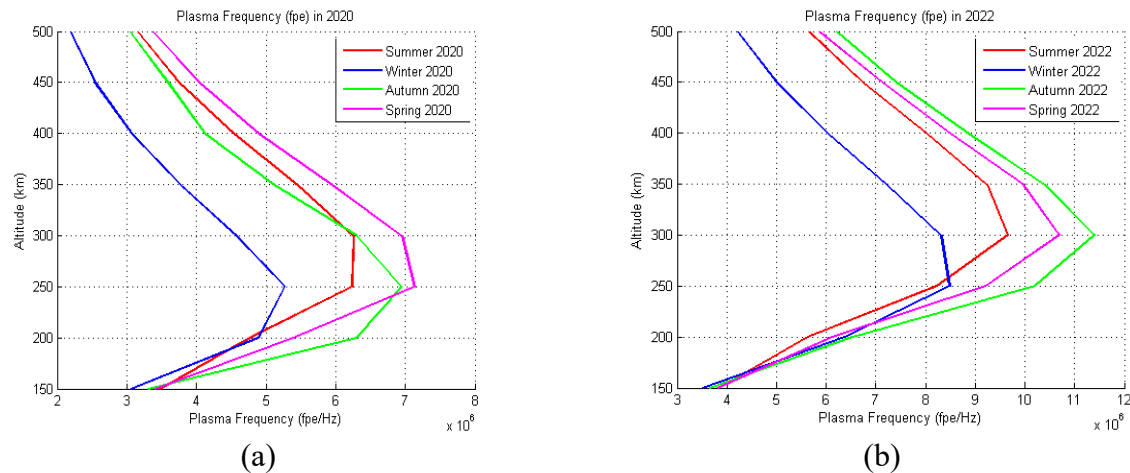


Figure 9: The Plasma frequency f_{pe} in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022 (a) Plasma frequency f_{pe} in 2020, (b) Plasma frequency f_{pe} in 2022.

The plasma frequency in the ionosphere is higher during the equinoxes (spring and autumn) than during summer and winter. This is because the equinoxes are characterized by a more balanced solar incidence angle and a more uniform distribution of solar radiation over the Earth. This leads to a more efficient ionization process in the ionosphere, and thus a higher electron density, which is reflected in an increase in the plasma frequency. In summer and winter, however, the unbalanced distribution of solar radiation and the less favorable incidence angle of sunlight led to less ionization and a lower electron density.

Figure 10 shows the population of charged particles enclosed within a Debye shielding region N_D during the years 2020 and 2022. There is a slight increase in the values from an altitude of 150 km to 350 km, after which a significant increase begins, reaching a peak at 500 km. The values were higher in winter and autumn than in the summer and spring.

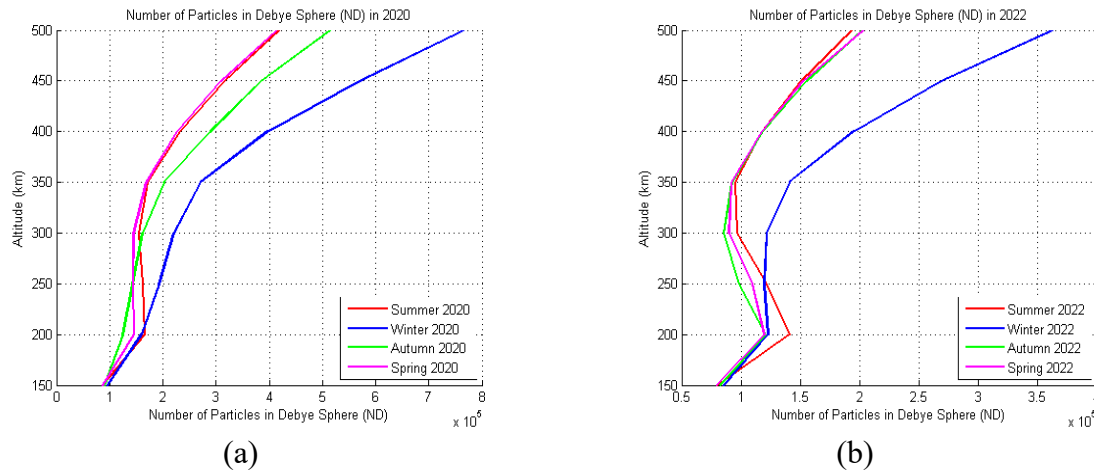


Figure 10: Number of particles in a Debye sphere N_D in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022 (a) The Debye sphere N_D in 2020, (b) The Debye sphere N_D in 2022

Also, Figure 10 explains the charged particles enclosed within the Debye shielding region N_D within the range of the F-layer of the ionosphere at an altitude of 150-500 km with an increase of 50 km during the years 2020 and 2022. (a) The population of charged particles enclosed within the Debye shielding region N_D in 2020, (b) The population of charged particles enclosed within the Debye shielding region N_D in 2022. N_D determines whether the plasma is ideal weakly bound ($N_D \ll 1$) or non-ideal strongly bound ($N_D \sim 1$).

Figure 11 shows a decrease in the value of the Plasma coupling parameter (Γ) as the altitude increased in the ionosphere F-layer during the year 2020, where the value of the coupled plasma was at its highest level at an altitude of 150 km, then decreased as the altitude increased, reaching its lowest value at an altitude of 500 km.

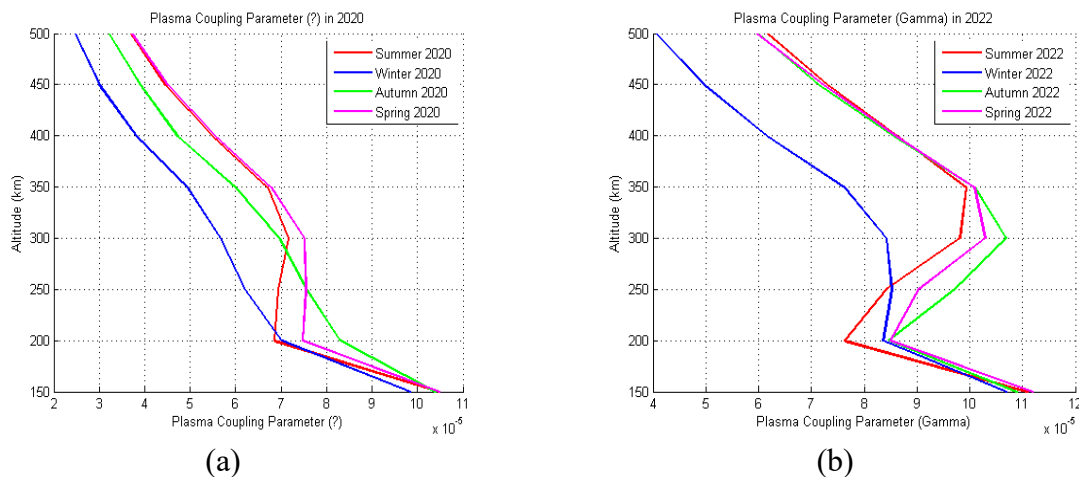


Figure 11: Plasma coupling parameter Γ in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022 (a) Plasma coupling parameter Γ in 2020, (b) Plasma coupling parameter Γ in 2022.

Also, indicators of coupling strength within ionospheric plasma within the range of the F-layer of the ionosphere at an altitude of 150-500 km, with an increase of 50 km during the years 2020 and 2022. (a) Plasma coupling parameter (Γ) in 2020, (b) Plasma coupling parameter (Γ) in 2022. plasma was weakly coupled ($\Gamma \ll 1$) in the ionosphere, where the thermal energy of electrons is much greater than the coulombic attractive energy due to high temperatures and low density.

Figure 12 shows a slight increase in the thermal velocity of the electron v_{te} from 150 km to 200 km, after which the sharp increase begins, reaching its peak at an altitude of 500 km. Thermal velocity of the electron v_{te} values were higher during winter and autumn than in summer and spring.

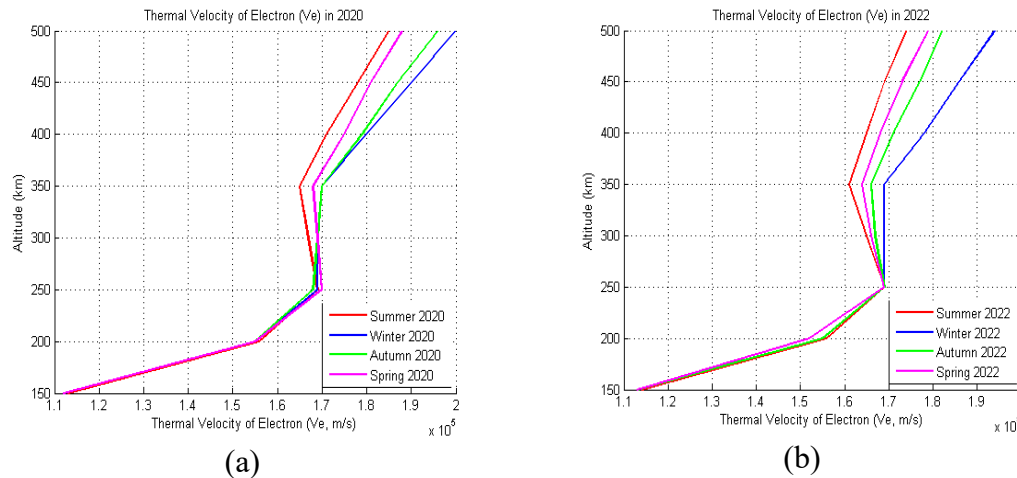


Figure 12: The thermal velocity of the electron v_{te} in the F-layer of the ionosphere at an altitude of 150-500 km during the years 2020 and 2022. (a) The thermal velocity of the electron v_{te} in 2020 (b) The thermal velocity of the electron v_{te} in 2022.

5. Conclusion

- The study revealed that electron temperatures (T_e) in the selected period increased with increasing altitude in the ionosphere.
- Electron density (n_e) in 2022 recorded higher levels compared to 2020, as a result of the increased number of sunspots and higher solar flux ($F_{10.7cm}$), reaching its peak during the fall and spring seasons.
- As the temperature increased, the Debye length (λ_{De}), Debye sphere particle count, and the electron thermal velocity v_{te} reached their highest levels at a height of 500 km.
- The mean free path of electrons increases with altitude, in parallel with the decrease in their collision frequency with neutral particles or ions, and the electron plasma frequency generally decreases at higher altitudes.
- The study shows that the plasma was weakly coupled ($\Gamma \ll 1$) during 2020 and 2022, in the ionosphere, where the thermal energy of electrons was much greater than the coulombic attractive energy due to high temperatures and low density.

Reference

- [1] P. Koucká Knížová "Ionosphere influenced from lower-lying atmospheric regions," *Frontiers in Astronomy and Space Sciences*, vol. 8, p. 651445, 2021.
- [2] T. Bozóki, "Solar cycle-modulated deformation of the Earth-ionosphere cavity," *Frontiers in Earth Science*, vol. 9, p. 689127, 2021.
- [3] K. Difar and A. S. Tasu, "Investigation in Communication Behavior of Ionosphere Regions," in *The Eighteenth International Conference on Networks*.
- [4] L. Liu, "Structure of post-midnight enhancements in electron density at the low latitude F-layer ionosphere," *Journal of Geophysical Research: Space Physics*, vol. 128, no. 4, p. e2023JA031376, 2023.
- [5] F. Arikan, S. Shukurov, H. Tuna, O. Arikan, and T. Gulyaeva, "Performance of GPS slant total electron content and IRI-Plas-STECh for days with ionospheric disturbance," *Geodesy and Geodynamics*, vol. 7, no. 1, pp. 1-10, 2016

- [6] G. Nicolaou, C. Ioannou, C. Owen, D. Verscharen, A. Fedorov, and P. Louarn, "How does the limited resolution of space plasma analyzers affect the accuracy of space plasma measurements?," *arXiv preprint arXiv:2505.09869*, 2025.
- [7] N. Imtiaz, A. Calabia, C. Anoruo, A. Zahid, C. Amory, and B. Adhikari, "Ionospheric Plasma Irregularities During Intense geomagnetic storms of Solar Cycle 25," in *Annales Geophysicae*, 2025 .
- [8] L. Conde, *An introduction to Plasma Physics and its space applications, Volume I: Fundamentals and elementary processes*. Morgan & Claypool Publishers, 2018.
- [9] Y. Lee, P. Aleynikov, P. de Vries, J.-K. Park, and Y.-S. Na, "Collision operator for electron runaway in cold weakly-ionized plasmas," *arXiv preprint arXiv:2509.03092*, 2025.
- [10] K. N. Drabo, M. Konate, R. Nakolemda, G. Sawadogo, E. Nanema, and F. Ouattara, "Modeling Total Electron Content and Critical Frequency at F1 and E Layer Boundary," *Asian J. Phys. Chem. Sci*, vol. 11, no. 4, pp. 37-42, 2023.
- [11] G. Tripathi, A. K. Singh, P. Singh, and A. K. Singh, "Response of low-latitude lower ionosphere during solar flare events over the complete solar cycle 24," *Acta Geodaetica et Geophysica*, pp. 1-22, 2025.
- [12] B. J. Ahmedov, B. S. Mirzaev, F. M. Mamatov, D. A. Khodzhaev, and M. K. Julliev, "Integrating of gis and gps for ionospheric perturbations in d-And f-layers using vlf receiver," *InterCarto, InterGIS*, vol. 26, pp. 547-560, 2020.
- [13] J. Mitchell *et al.*, "Energetic electron observations by Parker Solar Probe/IS $\odot$ IS during the first widespread SEP event of solar cycle 25 on 2020 November 29," *The Astrophysical Journal*, vol. 919, no. 2, p. 119, 2021.
- [14] N. Imtiaz, A. Calabia, C. Anoruo, A. Zahid, C. Amory, and B. Adhikari, "Ionospheric Plasma Irregularities During Intense geomagnetic storms of Solar Cycle 25," in *Annales Geophysicae*, 2025 .
- [15] H. S. Garee and K. A. Hadi, "Examining the seasonal correlation between SSN, T-Isindex, and F10.7 parameters during solar cycles 23 and 24," in *AIP Conference Proceedings*, 2023, vol. 2834, no. 1: AIP Publishing .
- [16] A. Abebe, "General Relativity as a Tool to Cosmology," *THE 3RD GONDAR SCHOOL OF SCIENCE & TECHNOLOGY (GSST-2012)*, p. 59.
- [17] E. Soltan, M. El-Metwally, and W. Moslem, "Double layers and solitary waves in Martian upper ionosphere," *Physica Scripta*, vol. 100, no. 4, p. 045601, 2025.
- [18] R. A. S. A. Alkareem, O. A. A. Dakhil, and B. M. Ahmed, "Study of plasma parameters using different voltages in an Ar/O₂ dielectric barrier discharge," in *AIP Conference Proceedings*, 2024, vol. 3097, no. 1: AIP Publishing .
- [19] H. Karami, S. Khorashadizadeh, R. Fallah, and A. Niknam, "Attosecond pulse generation by the interaction of intense laser pulse and hydrogen-like He⁺ ions in Debye plasma," *Optics Communications*, p. 131590, 2025.
- [20] Y. Zhang, H. Mao, Y. Li, and X.-Z. Tang, "Similarity for downscaled kinetic simulations of electrostatic plasmas: reconciling the large system size with small Debye length," *arXiv preprint arXiv:2501.14958*, 2025.
- [21] A. Demekhov, "The formation of large-scale plasma disturbances upon HF ionosphere heating: Dependence of the disturbance parameters on the frequency and power of HF radiation," *Radiophysics and Quantum Electronics*, vol. 65 ,no. 2, pp. 73-87, 2022.
- [22] V. Frolov, E. Andreeva, and A. Padokhin, "Spatial Structure of Plasma Density Perturbations Excited at Altitudes of the Upper and Outer Ionosphere During F 2-Layer Heating by Powerful HF Radio Waves," *Geomagnetizm i aëronomiâ* ,vol. 64, no. 3, pp. 363-385, 2024.
- [23] G. Nicolaou, C. Ioannou, C. Owen, D. Verscharen, A. Fedorov, and P. Louarn, "How does the limited resolution of space plasma analyzers affect the accuracy of space plasma measurements?," *arXiv preprint arXiv:2505.09869*, 2025.
- [24] J. Goswami and S. Kausik, "Investigating the Effects of Coupling in Strongly Coupled Dusty Plasma: A Comparative Study of Coupling Parameter Representations," *IEEE Transactions on Plasma Science*, 2024.
- [25] S. Malko *et al.*, "Low Velocity Proton Stopping Power Measurements in Warm Dense Carbon," in *2022 IEEE International Conference on Plasma Science (ICOPS)*, 2022: IEEE, pp. 1-2 .

- [26] L. B. Wilson III, K. A. Goodrich, D. L. Turner, I. J. Cohen, P. L. Whittlesey, and S. J. Schwartz, "The need for accurate measurements of thermal velocity distribution functions in the solar wind," *Frontiers in Astronomy and Space Sciences*, vol. 9, p. 1063841, 2022.
- [27] B. S. Zossi, T. Duran, F. D. Medina, B. F. de Haro Barbas, Y. Melendi, and A. G. Elias, "Evaluating F2-region long-term trends using the International Reference Ionosphere (IRI) model: is this a feasible approximation for experimental trends?," *Atmospheric Chemistry and Physics*, vol. 23, no. 21, pp. 13973-13986, 2023.
- [28] A. Pignalberi, M. Pietrella, and M. Pezzopane, "Towards a real-time description of the ionosphere: A comparison between international reference ionosphere (IRI) and IRI real-time assimilative mapping (IRTAM) models," *Atmosphere*, vol. 12, no. 8, p. 1003, 2021.
- [29] D. Bilitza, M. Pezzopane, V. Truhlik, D. Altadill, B. W. Reinisch, and A. Pignalberi, "The International Reference Ionosphere model: A review and description of an ionospheric benchmark," *Reviews of geophysics*, vol. 60, no. 4, p. e2022RG000792, 2022.
- [30] The Sunspot Cycle, "Marshall Space Flight Center, "NASA, USA, November, 2018. Available: <http://solarscience.msfc.nasa.gov/SunspotCycle>