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# Impact of the space weather events on the magnetosphere-plasmasphere-ionosphere system

## - Investigation of the 24 solar cycle maximum years -

## PhD thesis booklet

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ELTE
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Faculty of Science
Doctoral School of Environmental Sciences
**Budapest, 2024**

DOI: 10.15476/ELTE.2024.008

# 1. Introduction

Within the Earth's plasma environment (ionosphere, plasmasphere, magnetosphere), all regions are closely connected. Due to external forcing, perturbations can be observed in the individual plasma layers. All physical effects that cause measurable changes in the solar wind, the outer and inner magnetosphere, the ionosphere, and the thermosphere around the Earth are called space weather processes. The space weather events (ICME, SIR/CIR) that arrive at our Earth cause a so-called geomagnetic storm in the plasma environment of the planet.

The ionospheric F-layer has the highest electron density in the Earth's environment, which is why this layer is the most affected by changes in space weather events. The perturbations caused in the ionosphere during geomagnetic storms are called ionospheric storms, and their effects can be observed for 1-10 days. In terms of the variation with respect to a quiet day, we can define a positive (electron density increase) and a negative (electron density decrease) ionospheric storm. These storm events also have a major impact on modern technology on Earth, causing disruption to navigation systems, radio and satellite communications, for instance. For this reason, forecasting space weather storm events would be crucial. The general behaviour of the ionosphere during geomagnetic storms has been extensively studied over the years, but each space weather event and the processes involved are unique. Also, case studies with various instruments are rare in the literature, but they can be crucial for understanding the coupling mechanisms between different regions of the Earth's plasma environment during geomagnetic storms.

Since the exact effect mechanisms are not yet known, case studies like mine can provide new results, especially using multi-instrumental studies. Deepening our knowledge in this research area is of high importance if we want to predict the impact of space weather events.

# 2. Background, research objectives

A geomagnetic storm causes complex changes in the ionosphere on a global scale, known as an ionospheric storm. The changes also depend on the geomagnetic latitude. During my PhD research, I focused mainly on changes in the mid-latitude ionosphere (38°-55° N geographic latitude), the region above Europe. In order to understand the processes better, I also examined data from meridional station chains, as the ionospheric storm effect shows a north-south travelling pattern.

The primary task of my PhD research was the processing and complex interpretation of data from ground-based instruments (e.g., ionosondes) and satellites (e.g., ACE, Swarm, TIMED). My goal was to determine the exact impact (effects) of space weather phenomena on the Earth's physical environment and to extend our knowledge.

My main goal was to investigate the impact of the solar eruption events, such as Interplanetary Coronal Mass Ejection (ICME) and High-Speed Solar Winds (SIR/CIR - Stream Interaction Region/Corotating Interaction Region), in the complex Earth's thermosphere-ionosphere-plasmasphere system, and to identify the possible key processes causing the perturbations in the 24th solar cycle maximum period (2012-2015) over Europe.

My aim was also to determine how the impact on the terrestrial plasma environment depends on the strength and physical properties of the geomagnetic storm (magnetic field direction, plasma package velocity). My findings will contribute to the improvement of empirical space weather forecasting software.

# 3. Applied methodology and results

As a first step of my PhD research, I investigated in a case study the electron density changes in the sporadic E (Es) and F2 layers of the ionosphere caused by three geomagnetic storms related to ICMEs. Data were obtained from the ionosonde of the Széchenyi István Geophysical Observatory in Nagycenk and from international databases. I manually scaled the data from the ionograms and analysed the results also based on the suggestions of my supervisors [3].

As a continuation of these studies, I analysed the effects of the two intense ICME-induced geomagnetic storms over Europe using data from several instruments in order to accurately determine the relationships between the Earth's atmosphere-ionosphere-plasmasphere system. I used data from five stations, namely (from north to south) Juliusruh (JR, 54,6° N, 13,4° E), Pruhonice (PQ, 50° N, 14,6° E), Sopron (SO, 47,63° N, 16,72° E), Rome (RO, 41,8° N, 12,5° E) and Athens (AT, 38° N, 23,5° E). A combined analysis of the ionosonde/Digisonde F-layer electron density (foF2 parameter) and drift data, ratio of total electron content difference (rTEC) maps, TIMED (GUVI instrument $O/N_2$ measurements) and Swarm satellite, the ground-based global navigation satellite system, total electron content (GNSS TEC) data was performed. This provided a unique way of tracking the evolution and movement of the Midlatitude Ionospheric Trough (MIT-Midlatitude/Main Ionospheric Trough, which corresponds to the ionospheric footprint of the plasmapause (PP)). This cooperative research, which I organised, involved three Hungarian (Balázs Heilig, Veronika Barta and Árpád Kis) and two Czech (Jaroslav Urbar and

Daniel Kouba) colleagues. I coordinated the whole project, and prepared and processed the ionospheric data, rTEC maps and TIMED (GUVI) data myself. Balázs Heilig processed the Swarm data and calculated the MIT location. Jaroslav Urbar processed the GNSS TEC data for all station. Daniel Kouba manually corrected the Digisonde drift as professional user of these data. The gathered and analysed data were comprehensively discussed and summarized by me in the published paper [2].

In the next key step of my research, I investigated and compared the impact of perturbations related to ICMEs and SIR/CIRs in the complex Earth's thermosphere-ionosphere-plasmasphere system over Europe during the maximum period of the 24th solar cycle (November 2012 - October 2014). To do this, I created two individual lists of separate ICME- and separate SIR/CIR-induced events, validated by two of my research colleagues (Andrea Opitz and Zsuzsanna Dálya) from the Wigner Research Centre for Physics, who are also co-authors of my published paper. The list has also been published in the Mendeley Data Repository [4]. I have used this detailed and specific list as a basis this research and plan to do further studies. For this published research during my PhD, I selected 42 pure ICME and 34 pure SIR/CIR events. Each geomagnetic storm period was grouped by season, time of day and local time of $Dst_{min}$ and analysed using three different methods: linear correlation analysis using 4-hour averages of foF2 parameters and geomagnetic indices (1.), the percentage deviation from the reference values, the daily variation of the so-called deltafoF2 parameter (2.) and 3D plots: geomagnetic indices versus time versus deltafoF2 (3). The focus of the study was on the day of the main phase of the ICME- and SIR/CIR-induced geomagnetic storms, i.e. a 24-hour time interval was investigated [1].

Noteworthy, during my PhD studies, I mastered the manual evaluation of ionosonde/Digisonde data, which is currently managed by 3 researchers in Hungary and is done by a limited number of researchers worldwide. Thanks to this, I am participating in the Horizon 2022 T-FORS international project, as besides others, I am also using this knowledge.

# 4. Summary, theses

1) During three ICME-induced geomagnetic storms I analysed its ionospheric effects at Sopron station.
   a) I determined the percentage deviation of foF2 from the average quiet day value. I found a positive variation during the dawn hours, which was found to be unaffected by the geomagnetic storm strength, while the dusk effect (electron density increase around

sunset) clearly shows a proportional correlation with the geomagnetic storm strength by the three events using the same reference mean data which was computed from 5 quiet days.

b) I have shown two cases of an extreme decrease in the F-layer electron density during the main phase of the geomagnetic storm during the night hours over Europe: the 14 November 2012 storm, when the ionospheric storm phase was negative during the day and Dstmin <- 100 nT; the 17 March 2015 storm, when there was a positive ionospheric storm during the day and Dstmin < - 200 nT. The electron density of the F2-layer went below detectability level during the main phase of the geomagnetic storm at night: the plasma frequency decreased below 1.9 MHz, corresponding to an electron density of $4{,}5*10^4 \frac{1}{cm^3}$.

c) My results suggest that the presence of the Es-layer is not the cause of the F-layer "disappearance" during the night hours, as it does not blanket the F-layer. On the other hand, my results suggest that the magnitude of the geomagnetic storm has a noticeable effect on the activity of the sporadic E-layer: as the storm intensifies, the intensity of the Es-layer decreases, and during the most intense geomagnetic storm the foEs parameter falls below the detectability level.

d) The analysis suggests that the effect is most intense at mid-latitudes at night during the main phase of the geomagnetic storm, when negative ionospheric phases occurred during the daylight hours. Furthermore, my results confirm the generally accepted idea that only intense geomagnetic storms (Dstmin < -100 nT) can induce electron density decreases of such a scale that the layers disappear from the ionograms. The analysis of the h'F2 and foEs parameters supports this statement.

**Related publication: [2,3]**

2) I have developed a new method with the combined analysis of the European meridional station chain foF2, F-layer drift data, rTEC and Swarm measurements to detect, monitor and track the storm-time evolution of typical ionospheric structures (such as the Midlatitude Ionospheric Trough (MIT, which is the ionospheric footprint of the plasmapause)).

**Related publication: [2]**

3) In my investigations with the developed method, I detected the following phenomena over Europe during the main phases of the two largest geomagnetic storms of the 24th solar cycle:

a) On November 14, 2012, the negative phase in the foF2 data is very significant at all stations from 6 UT until afternoon. GUVI data suggest that this effect is associated with a very strong decrease in the $O/N_2$ ratio during the day.

b) Based on my investigations during the night of 14 Nov 2012, I found that the primary cause of the negative phase formation at JR, PQ, SO stations was the presence of a Midlatitude Ionospheric Trough (MIT). The rTEC maps and PQ drift measurements also confirm the presence of the trough at night. Moreover, based on the GUVI data, the daytime compositional disturbance zone seems to have extended towards the equator during the night, contributing to a more pronounced electron density drop. The MIT minima (coincident with the ionospheric footprint of the PP) is likely to have reached the Sopron latitude at the night of 14 November based on the rTEC maps and foF2 data. In contrast, AT and RO stayed within the plasmasphere, which was interpreted as an increase in foF2.

c) On 17 March 2015, a daytime positive ionospheric storm developed at all stations except JR.

   From a combined analysis of foF2, Swarm and GUVI data, I conclude that the negative phase at JR is mainly due to the movement of the Midlatitude Ionospheric Trough (MIT) towards the equator during the day, and not to a decrease in the $O/N_2$ ratio.

   It is assumed that the reason for the positive phase is mainly related to the Joule heating of the polar thermosphere, which, through enhanced equatorward winds, has lifted the plasma to altitudes where ion recombination is slower. The observed virtual altitude variations (h'F2) and vertical F-layer drift data, together with previous studies, also confirm the uplift scenario.

d) The Swarm data, together with the Digisonde drift measurements, supported my hypothesis that the extreme decrease in foF2 and TEC during the night of 17 March 2015 is related to the equatorward movement of MIT. Based on the Swarm data the equatorial side of MIT may have reached a geomagnetic latitude of less than 42°. Thus, I conclude that the unusually pronounced F-layer electron density decrease observed over the SO and PQ stations at night hours was caused by the presence of MIT in combination with a reduced $O/N_2$ ratio.

**Related publication: [2, 3]**

4) I used three different methods to investigate the impact of geomagnetic storms from different sources (ICME- or SIR/CIR-related) on the F-layer by statistical analysis of the parameter foF2.
    a) In the first method, I investigated the strength of the relationship between geomagnetic indices and 4-h averaged foF2 data and the linear relationship between them. My main conclusions are that winter ICME-driven events show a decreasing foF2 trend with linear fitting as a function of increasing geomagnetic indices in the Dawn and Morning groups. On the contrary, an increasing trend is observed in Afternoon/Dusk and Night groups by ICME-driven events. For SIR/CIR-driven events, we cannot determine an obvious trend as a result of the few numbers of events. This suggests that more than six events are needed to determine any trend in the foF2 parameter as a function of any geomagnetic index. In summer, a decrease in foF2 as a function of increasing geomagnetic activity is observed in most cases for both ICME- and SIR/CIR-driven events. Equinox events behave similarly to the summer ones, the difference is that the data points are more scattered, therefore the fitting is less reliable.

       The most significant correlations were between the Dst index and the foF2 parameter for the summer Night groups ($R = 0.81$). The linear fitting is the most reliable based on the RMSD between the Dst and foF2 with $RMSD = 0.28$ for the winter SIR/CIR Midnight group.
    b) In the second method, I investigated the diurnal evolution of the deltafoF2 parameter during two different types of geomagnetic storms. My results show that ICME-induced geomagnetic storms cause a larger and wider range of electron density perturbations in the electron density of the F2-layer both in negative and positive directions, while the effects caused by SIR/CIR-driven storms are more moderate and predictable.

**Related publications: [1]**

# 5. Scientific publications related to the topic of the thesis

### *Journal articles related directly to the PhD thesis*

[1] Berényi, K.A.; Opitz, A.; Dálya, Z.; Kis, Á.; Barta, V. (2023). *Impact of ICME- and SIR/CIR-Driven Geomagnetic Storms on the Ionosphere over Hungary*. Atmosphere 2023, 14, 1377. https://doi.org/10.3390/atmos14091377.

[2] Berényi, K. A., B. Heilig, J. Urbář, D. Kouba, Á. Kis, V. Barta, (2023). *Comprehensive analysis of the ionospheric response to the largest geomagnetic storms from solar cycle #24 over Europe*, Front. Astron. Space Sci., 24 April 2023 Sec. Space Physics Volume 10 – 2023, https://doi.org/10.3389/fspas.2023.1092850.

[3] Berényi, K. A., V. Barta, Á. Kis, (2018). *Midlatitude ionospheric F2-layer response to eruptive solar events-caused geomagnetic disturbances over Hungary during the maximum of the solar cycle 24: a case study*, Advances in Space Research 61, 1230–1243. https://doi.org/10.1016/J.ASR.2017.12.021.

### *Data repository publication related to the PhD thesis*

[4] Berényi, K.A., (2023). *Unique list of clear ICME- and SIR/CIR- related geomagnetic storm events from the maximum of 24 solar cycle (Nov 2012-Oct 2014)* 1. https://doi.org/10.17632/N245SCJZK4.1.

### *Other journal articles*

[5] Bór J.; G., Sátori; V., Barta; E., Prácser; T., Bozóki; A., Buzás; K., A. Berényi; D., Koronczay; Á., Kis; I., Lemperger et al. (2022). Hungarian contribution to the research of dynamic processes coupled with the upper atmosphere/ionosphere system (2019-2022) – IAGA DIVISION II: AERONOMIC PHENOMENA GEOMATIKAI KÖZLEMÉNYEK / PUBLICATIONS IN GEOMATICS 25 p. 57.

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### *Conference book proceedings*

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### ***Selected conference reports***

[12] Berényi, K.A.; Opitz, A.; Dálya, Z.; Kis, Á.; Barta, V. (2023). *Impact of ICME- and SIR/CIR-Driven Geomagnetic Storms on the Ionosphere over Hungary*. ESWW2023, Toulouse, France, 2023. nov.20-24.

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[14] Barta, V.; Berényi, K.; Buzás, A.; Kiszely, M.; Szabóné, A. K.; Szárnya, Cs. (2023). *T-FORS (TRAVELLING IONOSPHERIC DISTURBANCES FORECASTING SYSTEM) - magyar részvétellel megvalósuló H2022 projekt*, In: Bacsárdi, László; Barta, Veronika; Szárnya, Csilla; Wesztergom, Viktor (szerk.) Magyar Űrkutatási Fórum 2023: Az előadások kivonatai, Budapest, Magyarország: Magyar Asztronautikai Társaság 60 p. pp. 11.

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