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Earth's Lower Ionosphere impacted by High Class X-Ray Solar Flare Events

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Abstract

Solar activity, especially with its energetic events like solar flares and coronal mass ejections of high intensity, triggers abrupt and strong disturbances within near Earth surroundings, posing the potential hazard to numerous sophisticated technological systems both space-borne and ground-based on one hand, and putting at risk all living life on our planet on the other. Direct influences of events like geomagnetic storms and solar flares on human health were reported in literature. In this paper effects of high class X-ray solar flares form descending branch of 24th solar cycle were analyzed in terms of associated mid-latitudinal lower ionospheric disturbances over European sector, based on simultaneously monitored Very Low Frequency signals' perturbations as recorded by ground-based receiving system located in Belgrade, Serbia. Conducted numerical simulations revealed electron density increases of several orders of magnitude during maximal impact of analyzed solar flare events.

Key words: Solar activity, X-ray flares, ionosphere, VLF signal, perturbation

Introduction

Complex solar-terrestrial interactions between Sun and Earth have been in scientific focus for many decades, however only in recent past many governmental space agencies and observatories made their data, related to space weather, sun activity and satellite observations, both current and archived, publicly available, which combined with open access policies and in general broader information availability made space- and geo-sciences more approachable and more present in everyday life (see websites of major national space agencies, such as e.g. NOAA National Centers for Environmental Information, ESA Space Weather services, Center of Excellence in Space Sciences India, IISER Kolkata, Australian space weather forecasting center, Worldwide Archive of Low-Frequency Data and

Observations, Geostationary Operational Environmental Satellite (GOES) archive database, Royal Observatory of Belgium etc.).

Sun's continually emitted radiation, both of the electromagnetic and corpuscular nature, directly influence Earth's surroundings in terms of affecting and perturbing Earth's magnetosphere and ionosphere regions (e.g. Kelly 2009, Hayes et al. 2021, Rycroft et al. 2000 and references therein). Enhanced dependences on sophisticated technologies (like satellites, telecommunications, power grid systems) with globally increasing demands from modern societies made solar activity recognized and validated as potential hazard, to these systems and also to all living beings on our planet and space crews as well (e.g. Riley and Love 2017, Eastwood et al. 2017, Yasyukevich et al. 2018). An increasing overpopulation problems on Earth, in relation to more frequent and more intense severe weather conditions, as well with oft and at locations that are not so typical for their occurrences, along with general ongoing climate changes (e.g. Cramer et al. 2021, IPCC 2023, Martinich and Crimmins 2019), peaked interest of common people regarding possibly dangerous events of extraterrestrial origin (originating both from our solar system and beyond, like solar flares (SFs), coronal mass ejections (CMEs), gamma ray bursts (GRBs), etc.).

Complex solar activity, especially regarding energetic solar events, like intense SFs and CMEs and their interactions, is still unpredictable to solar physics, both regarding their occurrences and features. Such events, their interactions and impacts on near Earth environment are commonly presented as case studies, covering wide range of related phenomena and observational "points of view" (e.g. Manju et al. 2009, Sahai et al. 2007, Barta et al. 2022, Srećković et al. 2021, Kolarski et al. 2023).

Analysis and results

In this paper, active solar periods of the 24th solar cycle descending branch were investigated, with X-class X-ray solar flare events accompanied with CMEs given the special interest. Solar conditions during September 2017 and their geo-effective implications are presented as a case study, through observations conducted by employing Very Low Frequency (VLF) technology (e.g. Silber and Price 2017 and references therein). Ground-based Absolute Phase and Amplitude Logger (AbsPAL) system located in Belgrade (Serbia) at the Institute of physics (44.85°N; 20.38°E) operating in narrow-band mode was utilized for monitoring VLF signals' perturbations related to subionospheric propagation within Earth-ionosphere waveguide. Ionospheric parameters (Wait and Spies 1964) were retrieved by numerical modeling procedure (e.g. Silber and Price 2017 and references therein, Srećković et al. 2021, Kolarski et al. 2023, Thomson et al. 2005, McRar and Thomson 2004, Kolarski and Grubor 2014, Grubor et al. 2008, Šulić et al. 2016, Žigman et al. 2007, etc.) using Long Wave Propagation Capability (LWPC) software (Ferguson 1998). Soft X-ray flux (0.1-0.8 nm) solar data were taken from Geostationary Operational Environmental Satellite (GOES) archive database.

During 2017, Sun showed unusual activity in relation to both occurrences of solar flares and their strengths and of producing coronal mass ejections, taking into consideration how “late” in the solar cycle this activity emerged, practically right before the solar minimum between 24th and 25th SCs (in December 2019). In general, the 24th SC had notably decreased activity compared to several previous cycles. This SC had also the fourth smallest intensity since the 1st SC. Within SC with such “quiet” activity, and especially taking into consideration that is placed practically next to the solar minimum between 24th and 25th SCs, year of 2017 is striking primarily for two reasons: strongest of the SFs within entire 24th SC occurred during only one month of this year – September 2017 and also due to the abundance of produced SFs during this month (Tables 1 and 2). Aside especially active period during September (with 99 SFs reported, including 27 M-class and 4 X-class events), month of April (with 52 SFs reported, with 7 M-class and without X-class events) also stands out.

The most active period in 2017 was by far month of September, when 4 X-class SFs were reported: X2.2 and X9.3 occurred on September 6th, X1.3 occurred on September 7th and X8.2 occurred on September 10th. Two strongest among them, i.e. X9.3 and X8.2 are being the strongest reported SFs of the entire 24th SC. During September, the strongest M-class SFs of the year 2017 were reported: M8.1 occurred on September 8th and M7.3 occurred on September 7th. X-class SFs from September 2017 are listed in Table 3 (an original data, with applied scalar). Most of the activity and all of the strongest SFs of September 2017 are related to the same active region AR2673, which had very complex and unusual evolution producing in total 77 SFs, including 1 of B-, 45 of C-, 27 of M- and 4 of X-class events. During September 6th, 7th and 10th, R3 radio blackouts related to X-class SFs of X2.2, X9.3, X1.3 and X8.2 respectively, were reported. Related to accompanying CMEs, geomagnetic storms up to G4 were reported, as well.

It is interesting to note that SF X9.3 hasn’t been reported for two decades: event of similar strength dated back as far to November 6th, 1997 (X9.4) - interestingly also close to solar minimum, but on ascending branch of 23rd SC. One slightly weaker event occurred about one decade ago on December 5th, 2006 (X9) - interestingly also close to solar minimum and in descending branch of 23rd SC. Closest in time and of X-class, although significantly weaker in strength, was X2.7 reported on May 5th, 2015 - close to 24th SC solar maximum. Compared to X9.3 from September 2017, some weaker X-class SFs in period August-December were also reported over the years (e.g. in 2011 (X6.9), 2006 (X6.5), 2005 (X6.2) and 2005 (X5.4)) related to SCs’ branches and some significantly stronger SFs (e.g. in 2005 (X17+), 2003 (X28+) and 2001 (X20+)), related to SCs’ branches and activity maximum.

Earth's mid-latitudinal lower ionosphere impacted by high class X-Ray SFs from September 2017 was explored by remote sensing approach, employing ground-based equipment system located in Belgrade and using simultaneous multi-VLF signal monitoring technique. In terms of applied technology, Earth's lower ionosphere firmly responded to and followed incident soft X-ray radiation, with time delay corresponding to sluggishness of the ionosphere (Žigman et al. 2007, Appleton 1953), revealing intense perturbations both in amplitude and phase delays of recorded VLF signals. Perturbations monitored on VLF GQD signal related to high class X-Ray SFs from September 2017 and recorded by AbsPAL narrow-band system located in Belgrade are analyzed and presented in this study. The GQD signal is emitted from Skelton UK (54.72°N; 2.88°W) on frequency 22.1 kHz and arrives to Belgrade (44.85°N; 20.38°E) from north in NW-SE direction, propagating mostly over land, with Great Circle Path (GCP) of 1982 km, covering almost two time zones.

Solar X-ray irradiances of soft range (0.1-0.8 nm) corresponding to the most active days during September 2017 related to X-class solar flares are given in Figure 1. GQD signal amplitude and phase perturbations induced by these high class X-Ray SFs and recorded in Belgrade are given in Figure 2. Perturbations of GQD signal recorded in Belgrade, induced by these high class X-ray SFs, reached up to 8 dB in amplitude and up to a few tens of degrees in phase, compared to unperturbed ionospheric conditions. Based on recorded amplitude and phase perturbations, modeling of propagation parameters based on utilization of LWPC software was conducted, with goal that output parameters corresponding to modeled and input parameters corresponding to measured (real) conditions within waveguide match each other as close as possible (Kolarski et al. 2023, Kolarski et al. 2023b).

Modelling procedure was designed both for unperturbed and perturbed conditions, as best fitting as possible to real measured data using pairs of parameters sharpness β (km^{-1}) and reflection height H' (km) modelled for day time ionospheric conditions (Wait and Spies 1964), providing good agreement between real and modeled data.

Numerical simulations conducted in this research revealed electron density increases of several orders of magnitude during maximal impact of analyzed solar flare events compared to unperturbed ionospheric conditions. Estimated electron densities Ne (m^{-3}) at arbitrary height of 74 km are as follows: $2.06 \cdot 10^{11}$ m^{-3}, $1.15 \cdot 10^{12}$ m^{-3}, $1.76 \cdot 10^{10}$ m^{-3} and $2.12 \cdot 10^{11}$ m^{-3} in cases of X2.2, X9.3, X1.4 and X8.2, respectively. In case of strongest of SFs analyzed, this is almost 4 orders of magnitude higher compared to unperturbed value of $2.16 \cdot 10^{8}$ m^{-3} at the same reflection height. Electron densities related to maximal impact of high class X-ray SFs from September 2017, estimated at arbitrary height of 74 km, obtained according to conducted numerical modeling procedure are given in function of X-ray soft solar flux in Figure 3, indicated by black stars. Best fitting to general trend obtained from numerous previous studies based both on data recorded in Belgrade and from other research groups worldwide dealing with VLF technology is obtained for two SFs that occurred on 6th September, one of relatively weak intensity X2.2 and the other with very strong intensity X9.3, the strongest one of cases analyzed here.

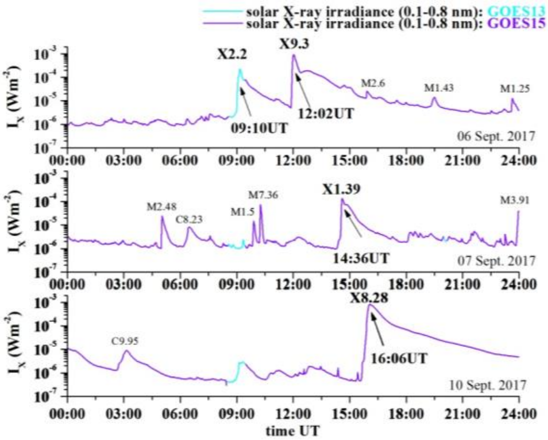

Fig. 1. Solar X-ray irradiance in soft range wavelengths (0.1-0.8 nm) during September 6th, 7th and 10th, 2017 (from upper to lower panel), as reported from GOES15 (violet) and GOES13 (light blue) satellites

Table 1. Solar activity of 24th SC descending branch in relation to X-ray solar flares (sources: NOAA National Centers for Environmental Information and Royal Observatory of Belgium)

year	av. yearly sunspot no.	no. of SF events				
		C-class	M-class		X-class	
2014*	113.3	1779	204	M1-M5=181	16	X1-X5=16
				M5-M9=23		X5-X9=0
2015	69.8	1368	125	M1-M5=115	2	X1-X5=2
				M5-M9=10		X5-X9=0
2016	39.8	320	15	M1-M5=12	/	X1-X5=0
				M5-M9=3		X5-X9=0
2017	21.7	237	39	M1-M5=33	4	X1-X5=2
				M5-M9=6		X5-X9=2
2018	7.0	13	/	M1-M5=0	/	X1-X5=0
				M5-M9=0		X5-X9=0
2019	3.6	32	/	M1-M5=0	/	X1-X5=0
				M5-M9=0		X5-X9=0
2020**	8.8	81	2	M1-M5=2	/	X1-X5=0
				M5-M9=0		X5-X9=0

* 24th SC max.: April 2014 and ** 24th SC min.: September 2020

Table 2. Solar activity during 2017 in relation to X-ray solar flare events (sources: NOAA National Centers for Environmental Information and Royal Observatory of Belgium)

2017	C-class SFs (∑ 237)		M-class SFs (∑ 39)		X-class SFs (∑ 4)		av. monthly sunspot no.
	no.	strength	no.	strength	no.	strength	
January	8	1 – 9.3	/	/	/	/	26.1
February	6	1.1 – 4.1	/	/	/	/	26.4
March	11	1 – 5.1	/	/	/	/	17.7
April	45	1 – 8	7	1.2 – 5.8	/	/	32.3
May	5	1 – 3.3	/	/	/	/	18.9
June	17	1 – 8	/	/	/	/	19.2
July	32	1 – 8.4	3	1.3 – 2.4	/	/	17.8
August	44	1 – 9.4	1	1.1	/	/	32.6
September	68	1 – 9.8	27	1 – 8.1	4	1.3 – 9.3	43.7
October	1	1	1	1.1	/	/	13.2
November	/	/	/	/	/	/	5.7
December	/	/	/	/	/	/	8.2

Table 3. X-class SFs from September 2017, from GOES15 database of soft solar flux component (0.1-0.8 nm)

Solar fare date	Class	Ix_{max} Time UT (hh:mm)	Ix_{max} (10^{-4} Wm^{-2})
6th Sept. 2017	X2.2	09:10	2.2658*
6th Sept. 2017	X9.3	12:02	9.3293
7th Sept. 2017	X1.3	14:36	1.3880
10th Sept. 2017	X8.2	16:06	8.2808

* GOES13 data

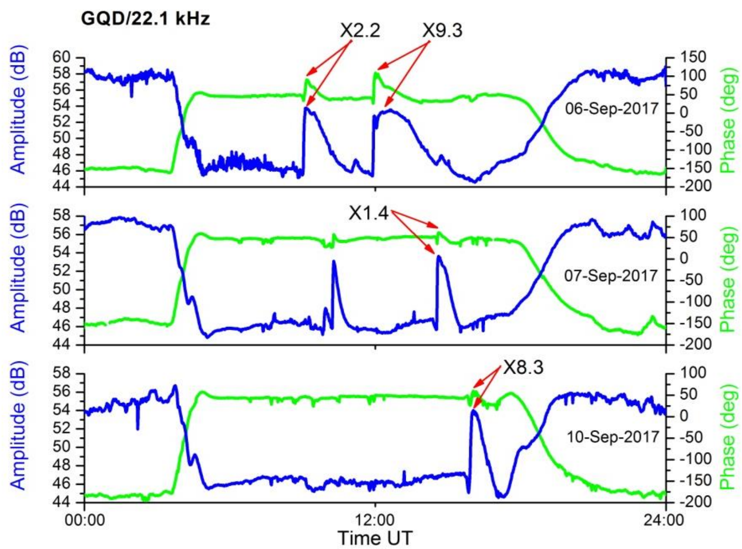

Fig. 2. GQD/22.10 kHz VLF signal perturbed phase (green) and amplitude (blue) during very active days of September 2017: 6th, 7th and 10th (from upper to lower panel) with perturbations related to high class X-Ray SFs indicated by red arrows, recorded by Belgrade VLF station

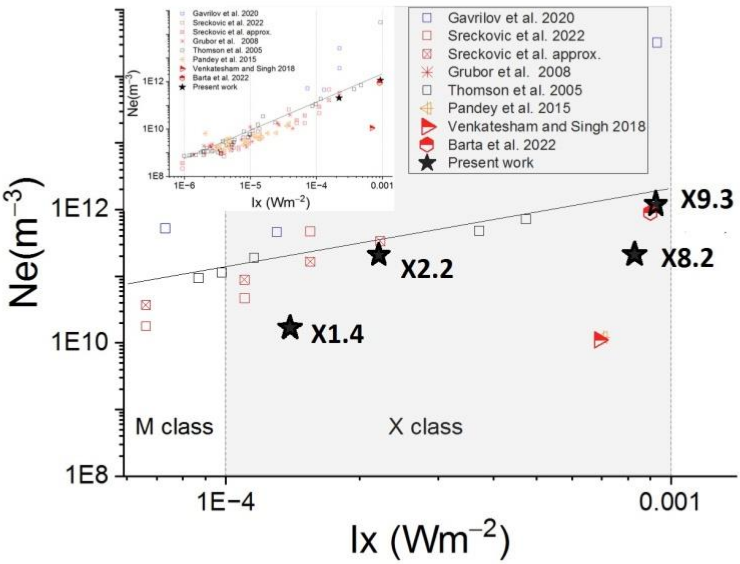

Fig. 3. Estimated electron densities Ne (m^{-3}) at arbitrary height of 74 km (black stars), related to high class X-ray SFs from September 2017, obtained by conducted numerical modeling procedure, in function of X-ray soft solar flux (0.1-0.8 nm) component

Discussion and Conclusions

Influences of high class X-ray SFs, belonging to descending branch of 24th SC, to mid-latitudinal lower ionosphere over Europe were investigated by employing ground-based technology for remote sensing using VLF signals transmitting within Earth-ionopshere waveguide.

Based on measured VLF signal perturbations registered in Belgrade, Serbia, numerical modeling procedure is conducted in order of retrieving propagation parameters of analyzed VLF signals and ultimately obtaining data related to lower ionopsheric parameters under intensely perturbed conditions. Influences of four SF events of X-class from September 2017, as the most active period in terms of solar activity producing high X-class SFs over entire 24th solar cycle, i.e. impact of X1.4, X2.2, X8.2 and X9.3 events to VLF radio signal propagation disturbances monitored on GQD/22.1 kHz signal were analyzed in detail and presented.

During maximal X-ray irradiances of analyzed SF events, observations showed that caused changes in GQD signal amplitude reached up to 8 dB and up to a few tens of degrees in phase, as compared to unperturbed ionospheric conditions. Based on measured data, numerical simulations gave output providing good agreement between real and modeled data. Estimated electron density during perturbed ionospheric states corresponding to maximal impact of analyzed SFs showed increases of several orders of magnitude, as compared to unperturbed ionospheric conditions, with maximal value of $1.15 \cdot 10^{12}$ m^{-3} at arbitrary height of 74 km in case of strongest X9.3 SF event.

Investigations of ionopsheric responses to energetic solar phenomena, like high class SFs presented in this paper, are not only important for exploration of both magnetospheric plasma properties and ionospheric physics, but also for obtaining deeper insights into and for potential predictions of extreme space weather effects on modern society actions.

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