Flux Variations in Lines of Solar EUV Radiation Beyond Flares in Cycle 24

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Abstract. Studies in the extreme ultraviolet (EUV) and X-ray ranges of the solar spectrum are important due to the active role of radiation of these ranges in the formation of the Earth's ionosphere. Photons of the EUV range are completely absorbed in the upper layers of the Earth's atmosphere and induce the excitation, dissociation, and ionization of its different components and, finally, the atmospheric heating. From the archive data of the EUV Variability Experiment of the Solar Dynamics Observatory (SDO/EVE), we formed series of diurnal values of the background fluxes radiated beyond flares in the EUV lines HeII (30.4 nm), HeI (58.4 nm), CIII (97.7 nm), and FeXVIII (9.4 nm) in cycle 24 (from 2010 to 2017). These fluxes are compared to the corresponding values of the radio flux $F_{10.7}$ at a wavelength of 10.7 cm and the background radiation flux $F_{0.1-0.8}$ in the X-ray range between 0.1 and 0.8 nm measured onboard the GOES-15 satellite of the Geostationary Operational Environmental Satellite system. Comparative analysis has shown that the solar radiation in individual lines of the EUV range and the fluxes $F_{10.7}$ and $F_{0.1-0.8}$ are closely interrelated.

Key words. EUV-fluxes of the Sun: SXR-fluxes of the Sun: SDO/EVE data.

1 INTRODUCTION

Solar ultraviolet (UV) radiation is a main source of energy in the Earth's upper atmosphere. It influences the geocosmic medium and affects the operation of satellites and communication and navigation systems. UV radiation changes on different time scales, from several seconds to a year, and over an 11-year solar cycle. Solar short-wavelength radiation forms in the upper chromosphere, the transition zone, and the corona, while the entire short-wavelength range accounts for only 9% of the total energy. However, it is impossible to model the state of the Earth's upper atmosphere without observations and prognoses of the values of the solar radiation fluxes in the UV and X-ray spectral ranges. Variations in the short-wavelength (SW) radiation are determined to a considerable extent by the entire area and the evolution of structural formations in the solar atmosphere. The emergence and development of active regions and faculae areas are superimposed on the radiation of "the quiet Sun" and enhance the observed variations in the UV range (Makarova et al., 1991; Lean, 1987).

Short-term variations in flares induce changes of up to 60% in the UV range and three orders of magnitude in the soft X-ray (SXR) range. Long-term changes in the solar cycle cause changes to the radiation fluxes in the corresponding SW ranges from tens of percent to several times.

The era of extra-atmospheric observations of the Sun, i.e., observations made with instruments onboard balloons and rockets, began in the late 1950s. The first emission in the hard X-ray range was detected during a flare in 1958 by Peterson and Winckler (1959). At present, extreme ultraviolet (EUV) and soft X-ray (SXR) fluxes are continuously monitored by instruments onboard the TIMED, SEE, SDO, and GOES satellites (Woods et al., 2012). The GOES-15 satellite of the Geostationary Operational Environmental Satellite system is currently the main source of data on X-ray flares on the Sun. It is expected that such observations will be continued with a focus on surveys of the thermosphere and ionosphere of the Earth (Woods, 2008; Benz, 2017).

Variations in the SW radiation lead to changes in the Earth's thermosphere and ionosphere. Photons of UV radiation are absorbed in the upper layers of the terrestrial atmosphere and induce ionization and dissociation of the atmospheric components, which substantially influences processes in the atmosphere and ionosphere (e.g., Ivanov-Kholodnii and Nusinov, 1987). The scale of changes was illustrated by Schmidtke et al. (1981): a 30% decrease in the total UV flux is equivalent in value to the energy flux entering the upper atmosphere during a strong magnetic storm.

According to Roble (1983), if the HeII line (30.4 nm) is removed from the solar spectrum, the exospheric temperature at the upper boundary will decrease by 88 and 129 K in the periods of the solar activity minimum and maximum, respectively. Thus, the change in the UV-radiation fluxes may induce a substantial response in the thermosphere, including variations in the temperature and the optical thickness in different spectral ranges and, consequently, in the thermospheric energy (Kockarts, 1981). The total electron content (TEC) in the ionosphere is determined by the solar EUV radiation.

The data of SW-radiation flux beyond flares substantially (several-fold) varies during the activity cycle and, naturally, depends on the general level of solar activity (Bruevich and Yakunina, 2015). In the paper we analyze the data from daily measurements of the fluxes, which are not related to flares, in four UV lines - HeI, HeII, CIII, and FeXVIII at 58.4, 30.4, 97.7, and 9.4 nm, respectively. The data were taken from the SDO/EVE observational archive.

According to the papers by Lemen et al. (2012) and Ivanov-Kholodnii and Nikol'skii (1969), the largest concentration of ions emitting in the considered lines is reached at essentially different altitudes (and under different temperatures) in the solar atmosphere. The lines HeII (30.4 nm; log T is equal to 4.75) and CIII (97.7 nm; logT is equal to 4.68) form in the transition zone, while the lines HeI (58.4 nm; log T is equal to 4.25) and FeXVIII (9.4 nm; log T is equal to 6.7-7.0) form in the chromosphere and the corona, respectively.

Table 1 contains the temperatures (column 4) in regions of the solar atmosphere (column 5) in which the ions radiating in the specified lines are formed. Since not all of the SDO/EVE observations completely cover cycle 24, the observational period is shown in column 6. Column 7 contains the estimate of variations of the mean level of the flux beyond flares for each of the lines from the minimum to the maximum of cycle 24 (expressed in W/m2). Figure 1 presents variations in the UV-radiation fluxes in the chosen spectral lines for 2010-2017. The results of ground-based observations of the radio flux $F_{10.7}$ are shown for comparison. For the growth phase of cycle 24 (2010-2014), the fluxes in the HeII (30.4 nm) and FeXVIII (9.4 nm) lines are presented. The fluxes in the CIII (97.7 nm) and HeI (58.4 nm) lines entirely cover cycle 24. Figure 1 and Table 1 show that the EUV-radiation fluxes in the chosen lines change in different ways: the largest variations are observed for the FeXVIII (9.4 nm) line (a twofold change from the minimum to the maximum of cycle 24), while the smallest variations are exhibited by the most geoeffective line of the EUV spectrum, HeII (30.4 nm), (by 26% from the minimum to the maximum of cycle 24).

The purpose of the paper is to study the variability of the solar EUV-radiation fluxes and their interrelation with the flux at a wavelength of 10.7 cm and background X-ray radiation in a range of 0.1-0.8 nm in solar activity cycle 24.

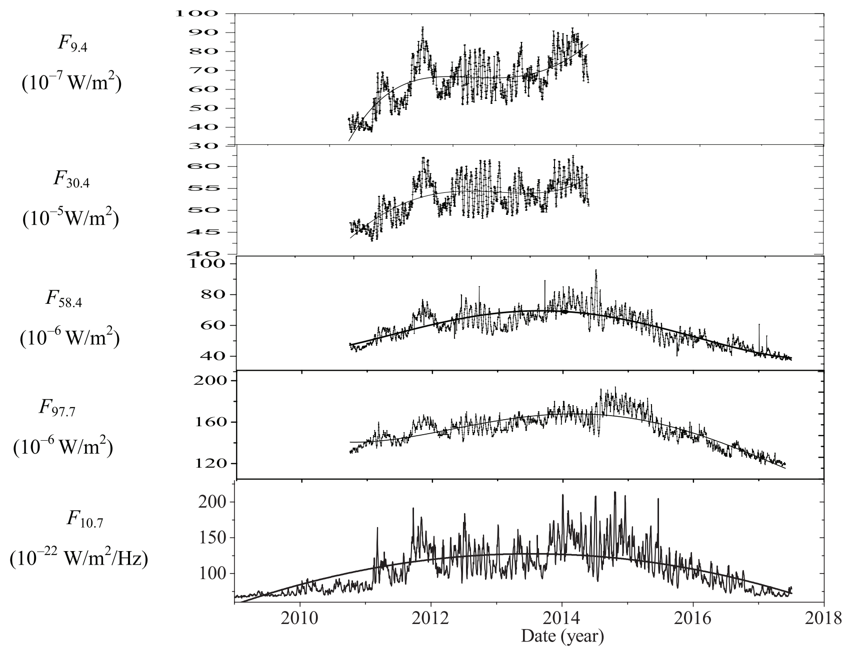

Figure 1: Background values of the fluxes in lines of the EUV range from the SDO/EVE daily observations and the radio flux at a wavelength of 10.7 cm in cycle 24.

2 FLUXES IN LINES AT THE WAVELENGTH 58.4, 30.4, 97.7, AND 9.4 NM FROM OBSERVATIONAL DATA OF THE SDO/EVE EXPERIMENT

The objectives of the EUV Variability Experiment of the Solar Dynamics Observatory (SDO/EVE) are as follows: to study solar EUV radiation in more than 50 lines and spectral ranges, to study its variability on different time scales to improve forecasting capabilities, and to study the flare activity effect in the EUV range. The EVE instruments onboard the SDO satellite measure the solar EUV radiation from 0.1 to 105 nm with a spectral resolution of 0.1 nm and a time interval of 10 s. A spectral resolution of at least 0.1 nm is required to distinguish the main bright emission lines, which improves the quality of the subsequent detailed prognosis in modeling of the Earth's

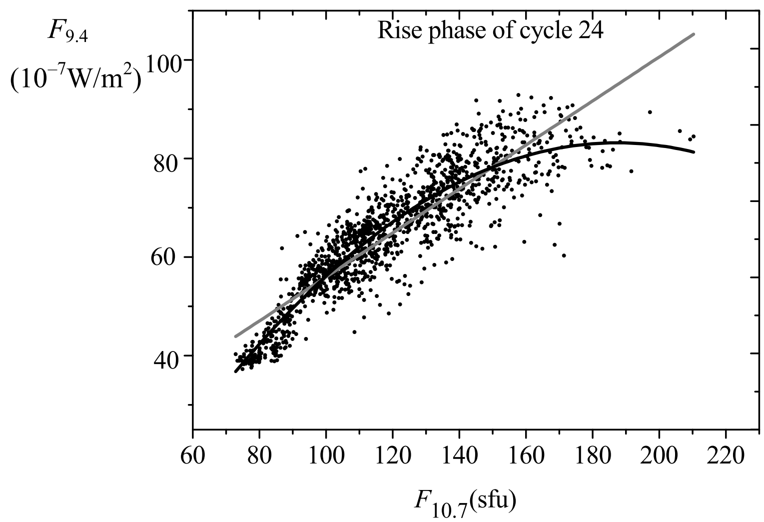

Figure 2: Background flux in the FeXVIII line (9.4 nm) with respect to the radio flux at the 10.7 cm wavelength in the growth phase of cycle 24.

ionosphere and thermosphere (Woods et al., 2010). Despite the success of numerical models describing variations in the density and the temperature of the ionosphere, the problem of verifying these models by observations remains. The values of the solar EUV and X-ray radiation fluxes obtained from observations turn out to be somewhat smaller than those required to explain the actual ion density values in the lower ionosphere ($\sim$ 110 km) (Solomon et al., 2013; Solomon, 2016). The regions of the formation of emission lines in the solar atmosphere depend on the temperature. Small variations in the UV and X-ray radiation connected with appearing and disappearing groups of spots in active regions and with variations of activity in the solar cycle and large flares cause noticeable changes in the UV and X-ray indices of activity.

Simon (1981) showed that, according to the measurements in cycle 20, the amplitudes of variations in the UV radiation strongly depend on the wavelength: they decrease increasing wavelength (a twofold difference, less than 1% for intervals of 135-175 and 330-340 nm, respectively). Rottman (1988) reports an analogous result for solar activity cycle 21: there is a twofold change in radiation variations from the maximum to the minimum in the range 121.6-150 nm and a decrease to 20% for$\lambda = 190$ nm.

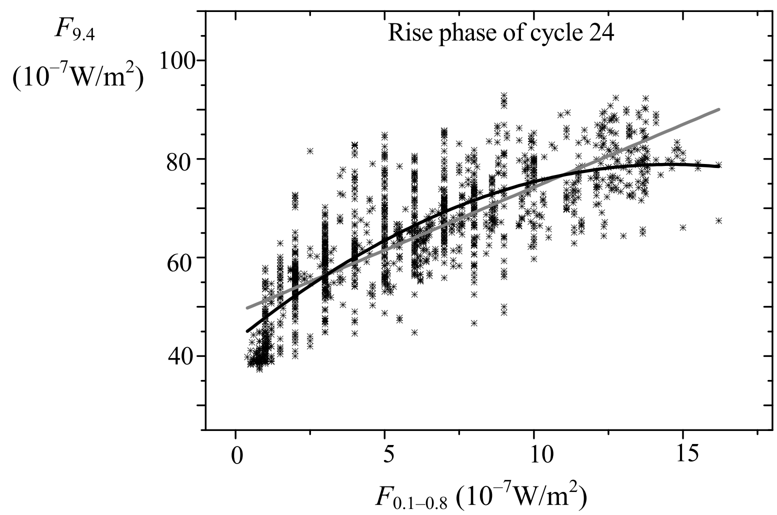

Figure 3: Background flux in the FeXVIII line (9.4 nm) with respect to the background X-ray flux in a range of 0.1-0.8 nm in the growth phase of cycle 24.

The GOES, SDO, ACE, SOHO, Proba 2, and STEREO satellites, combined with ground-based data such as the $F_{10.7}$ index, are used for real-time TEC forecasting (Hinrichs et al., 2016). Didkovsky and Wieman (2014) and Jee et al. (2014) analyzed the TEC response to the EUV-radiation variations in the 30.4-nm line in a period of 1995-2013. It turned out that the EUV-radiation fluxes exhibit considerable relative variations in activity, which may reach 20% in the cycle.

Note than in Table 1 the value of 1 sfu is equal to $10^{-22}W/m^2/Hz$, The temperatures (column 4) are taken from the Lemen et al. (2012) and Ivanov-Kholodnii and Nikiol'skii (1969).

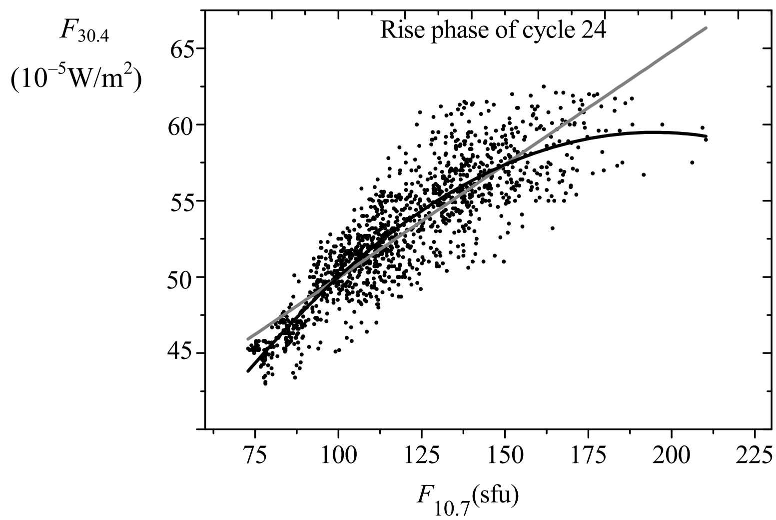

Figure 4: Background flux in the HeII line (30.4 nm) with respect to the radio flux at the 10.7-cm wavelength in the growth phase of cycle 24.

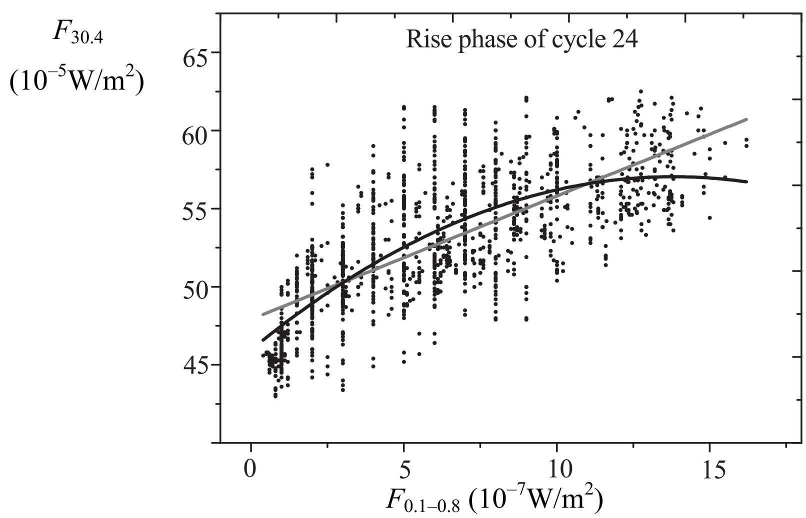

Figure 5: Background flux in the HeII line (30.4 nm) with respecgt to the X-ray flux in a range of 0.1-0.8 nm in the growth phase of cycle 24.

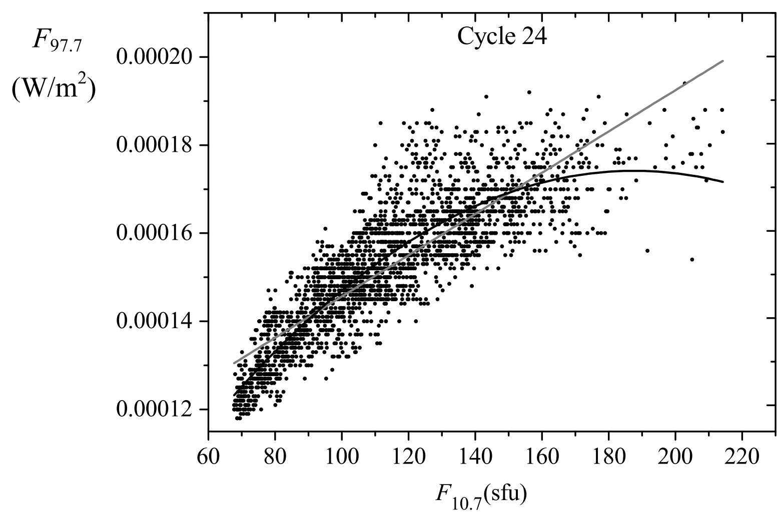

Figure 6: Background flux in the CIII line (97.7 nm) with respect to the radio flux at the 10.7-cm wavelength in cycle 24.

3 CONNECTION OF THE FLUXES IN EUV LINES WITH THE FLUXES AT A WAVELENGTH OF 10.7 CM AND AN INTERVAL OF 0.1-0.8 NM

The high correlation degree of $F_{10.7}$ with all of the main activity indices suggests that the indices strongly depend on the plasma parameters where these fluxes are formed, while the regions of their formation are spatially close. $F_{10.7}$ monitoring is a useful instrument to predict variations in the solar coronal UV radiation, which changes by an order of magnitude in dependence on the number and the brightness of the solar active regions. UV fluxes play an important role in the heating of the Earth's atmosphere and, consequently, in forming the Earth's climate. Since the total flux $F_{10.7}$ correlates rather well with the integrated fluxes in the UV and EUV ranges of the solar spectrum, it can also be used as a basic index to predict fluxes in these intervals of the solar spectrum. The radio$F_{10.7}$ from the entire solar disk can be divided into

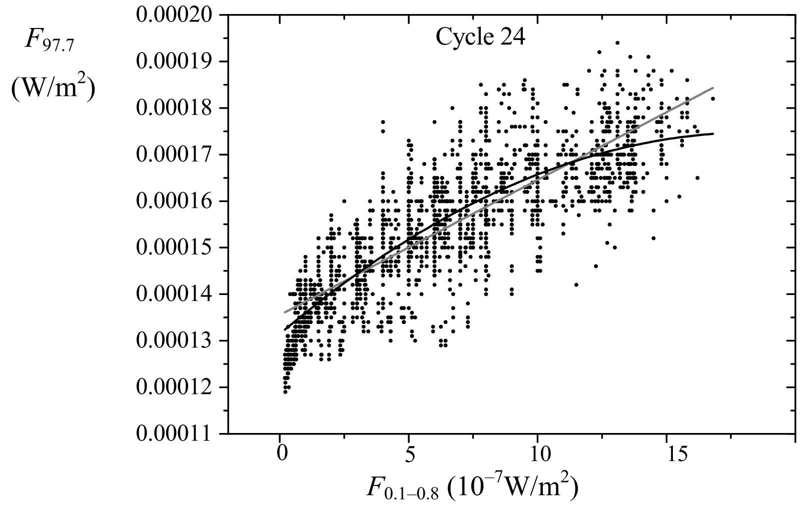

Figure 7: Background flux in the CIII line (97.7 nm) with respect to the background X-ray flux in a range of 0.1-0.8 nm in cycle 24.

three components (according to the characteristic time scales): (1) events connected with flare activity of less than one hour; (2) slow intensity variations lasting several years that are connected with the evolution of active regions in a solar cycle (the S component); (3) the lowest $F_{10.7}$ level, below which the intensity never drops, i.e., the so-called quiet-Sun level. According to observations, there is a close correlation between the S component of the radio emission at 10.7 cm with fluxes in the UV lines (Tapping, 2013). The flux at a wavelength of 10.7 cm grows with increasing temperature, material density, and magnetic fields, which makes it a good indicator of the general level of solar activity (Bruevich and Yakunina, 2015). In the paper, we use data on daily SDO/EVE observations of the background fluxes in the EUV range and data on daily observations of $F_{0.1-0.8}$ performed beyond flares in cycle 24, which we obtained from the archive of the GOES-15 satellite data. For these observations, we built the linear and quadratic dependences of the EUV fluxes in different lines on both the radio$F_{10.7}$ and the soft X-ray $F_{0.1-0.8}$ for the growth phase of cycle 24 (2010-2014) and the entire cycle 24 (2010-2017). These dependences are presented in Figs. 2-9; the linear and quadratic regressions are shown with gray and black solid lines, respectively.

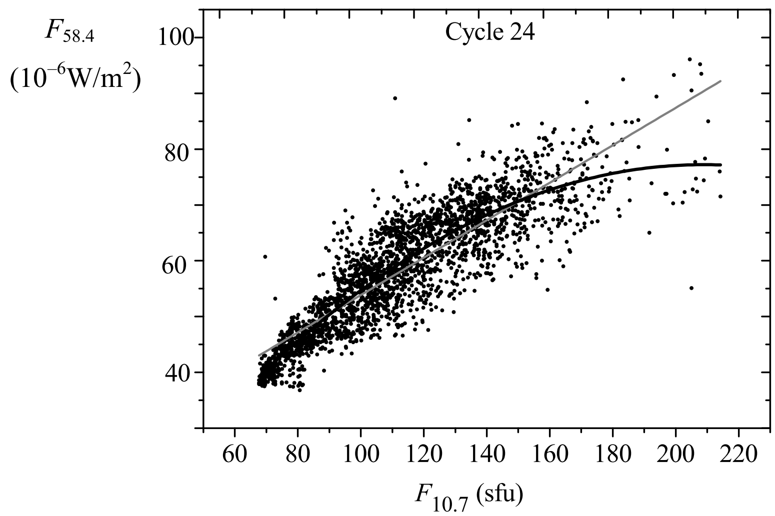

Figure 8: Background flux in the HeI line (58.4 nm) with respect to the radio flux at the 10.7-cm wavelength in cycle 24.

Table 2 contains the quadratic regression coefficients (A, B1, and B2) for the dependences of the Fline fluxes in four analyzed lines of the EUV range on the $F_{10.7}$ value and the background $F_{0.1-0.8}$ in cycle 24. They correspond to the following equations:

$$F_{Line} = \ A + B1 \cdot F_{10.7} + B2 \cdot F_{10.7}^2$$

and

$$F_{Line} = \ A + B1 \cdot F_{.1-0.8} + B2 \cdot F_{0.1-0.8}^2$$

where A, B1, and B2 are the quadratic regression coefficients,F_{Line} are the fluxes in analyzed lines, $F_{10.7}$ is the radio flux at a wavelength of 10.7 cm, and $F_{0.1-0.8}$ is the X-ray flux beyond flares in a range of 0.1-0.8 nm. The values of the residual sum of squares (RSS, which is a measure of the difference between the observational data and the regression-line model) were estimated for the linear and quadratic regressions. The small RSS value indicates a close fit with the data by the model. In our case, the RSS values are smallest when the dependence of the activity index on the $F_{10.7}$ value is described by second order polynomials.

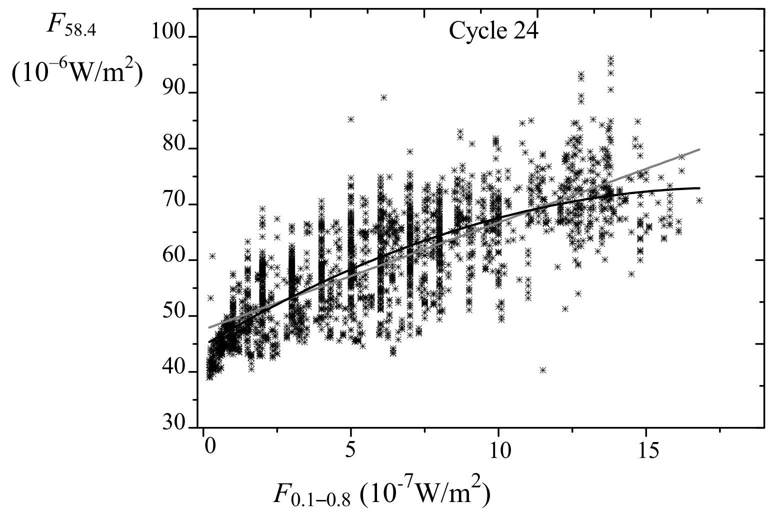

Figure 9: Background flux in the HeI line (58.4 nm) with respect to the background X-ray flux in a range of 0.1-0.8 nm in cycle 24.

Table 2 shows that there is a strong correlation between the UV fluxes in the analyzed lines and the $F_{10.7}$. The corresponding correlation with the$F_{0.1-0.8}$ turned out to be much weaker.

4 Conclusions

Solar EUV-radiation is the main source of heating and ionization of the upper layers of the terrestrial atmosphere. It is completely absorbed by the Earth's atmosphere and governs the main parameters of the upper atmosphere. It is important to study the EUV-radiation variations (diurnal and long-term in an 11-year cycle), because they contain information on the solar chromosphere and corona and the processes during solar flares. Our analysis yielded the following results. From the SDO/EVE observational data archive, we formed four data sets containing the diurnal values of the background fluxes in the lines HeI (58.4 nm), HeII (30.4 nm), CIII (97.7 nm), and FeXVIII (9.4 nm) during the 2010-2017, 2010-2014, 2010-2017, and 2010-2014 periods, respectively. The variations of these fluxes in the considered lines depend on

Table 1: Data on the background fluxes in lines during observations of the SDO/EVE experiment in the line-forming regions

N	Ion	λ, nm	logT_i	Line formation	Observations	Flux range, W/m^2
1	2	3	4	5	6	7
1	FeXVIII	9.4	7.0	Corona	09.2010-06.2014	4E-6 - 8E-6
2	HeII	30.4	7.0	Trans. zone	09.2010-06.2014	4.6E-5 - 5.8E-5
3	HeI	58.4	4.25	Chromosp.	09.2010-06.2017	4.65E-5 - 7.6E-5
4	CIII	97.7	4.68	Trans. zone	09.2010-06.2017	1.35E-4 -1.8E-4
5	$F_{10.7}$	10.7 cm	6.0-6.5	Corona	01.2008-06.2017	67 sfu - 260 sfu

Table 2: Quadratic regression coefficients for the dependences of the fluxes in four lines of the EUV range on $F_{10.7}$ and the background flux $F_{0.1-0.8}$

$F_{Line} - F_{10.7}, F_{0.1-0.8}$	A	B1	B2	σA	$\sigma B1$	$\sigma B2$
1	2	3	4	5	6	7
$F_{30.4} - F_{10.7}$	1.95E-4	4.11E-6	-1.05E-8	1.03E-5	1.69E-7	6.75E-10
$F_{30.4} - F_{0.1-0.8}$	4.59E-4	1.60E2	-5.81E7	2.24E-6	7.37	3.1E3
$F_{9.4} - F_{10.7}$	-4.12E-6	1.33E-7	-3.54E-10	2.66E-7	4.36E-9	1.74E-11
$F_{9.4} - F_{0.1-0.8}$	4.31E-6	4.92	-1.69E6	5.72E-8	0.19	1.29E5
$F_{97.7} - F_{10.7}$	4.94 E-5	1.33E-6	-3.54E-9	2.11E-6	3.56E-8	1.45E-10
$F_{97.7} - F_{0.1-0.8}$	4.94E-5	1.33E1	-3.55E6	2.11E-6	3.57E-1	1.45E4
$F_{58.4} - F_{10.7}$	-5.95E-6	7.97E-7	-1.91E-9	1.37E-6	2.33E-8	9.53E-11
$F_{58.4} - F_{0.1-0.8}$	4.47E-5	3.17E1	-8.9E6	0.33E-6	1.11	7.52E4

the wavelength to different extent; they are presented in Fig. 1 and Table 1. Regression analysis showed that the radiation in the considered lines of the EUV range was closely connected with the radio $F_{10.7}$ and the flux in the soft X-ray range. We used second-order regression equations, since the quadratic regression yields a RSS value substantially smaller than that produced by the linear regression. Table 2 shows the results of the analysis. From the results of regression analysis (Table 2), the values of the fluxes in the considered lines can be retrieved with the use of the data on $F_{10.7}$ and $F_{0.1-0.8}$ available in real-time mode.

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