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Title: Validation of Extreme Ultraviolet Emission Spectra During Solar Flares

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Abstract

X-rays and extreme ultraviolet (EUV) emissions from solar flares rapidly change the physical composition of the Earth's thermosphere and ionosphere, thereby causing space weather phenomena such as communication failures. To predict the effects of flare emissions on the Earth's upper atmosphere, numerous empirical and physical models have been developed. We verify the extent of reproducing the flare emission spectra using a one-dimensional hydrodynamic calculation and the CHIANTI atomic database. To verify the proposed model, we use the observed EUV spectra obtained by the extreme ultraviolet variability (EVE) on board the Solar Dynamics Observatory (SDO). We examined the "EUV flare time-integrated irradiance" and "EUV flare line rise time" of the EUV emissions for 21 events by comparing the calculation results of the proposed model and observed EUV spectral data. The proposed model succeeded in reproducing the EUV flare time-integrated irradiance of the Fe VIII 131 Å, Fe XVIII 94 Å, and Fe XX 133 Å, as well as the 55 to 355 Å and 55 to 135 Å bands. For the EUV flare line rise time, there was acceptable correlation between the proposed model estimations and observations for all Fe flare emission lines. These results demonstrate

that the proposed model can reproduce the EUV flare emission spectra from the emitting plasma with relatively high formation temperature. This indicates that the physics-based model is effective for the accurate reproduction of EUV spectral flux.

Keywords

Solar flare, X-ray emission, EUV emission, Space weather

Main Text

1. Introduction

To freely utilize outer space as a place for deploying advanced space activities, a common fundamental system, called space infrastructure, is required. To build and use a space infrastructure safely, it is important to accurately grasp the current state of the solar-terrestrial environment, which is strongly influenced by solar activities. Among the solar activities, solar flares have the greatest influence on the solar-terrestrial environment. When solar flares occur, powerful electromagnetic radiation and large amounts of high-energy particles are released. Among these, it is well known that the

X-ray and extreme ultraviolet (EUV) emissions of the solar flares, in particular, influence the Earth’s communication network. When X-ray and EUV emissions from solar flares reach the Earth’s upper atmosphere, especially the D layer of the ionosphere, oxygen and nitrogen in the D layer are ionized. Consequently, the electron density in the D layer increases rapidly, and radio waves (especially at high-frequency ranges) propagating through the D layer are absorbed. This phenomenon is called the Dellinger phenomenon (Dellinger 1937), which is widely known as one of the sudden ionospheric disturbances (SIDs). Solar flare emissions reach the Earth in approximately 8 min, and the lead time from solar flare to SIDs is extremely short. Therefore, it is important that the solar irradiance, especially X-ray and EUV emissions, be constantly monitored to minimize the adverse effects of SIDs.

In general, it is considered that SIDs are caused by the occurrence of solar flares of the M-class or higher, and can be predicted using the flare class. However, it has been reported that SIDs have occurred from C-class flare, and have not occurred from X-class flares. These observational results suggest that the flare emission contributing to the occurrence of SIDs is not necessarily proportional to the X-ray intensity. To verify

what solar flare emission wavelengths influence the occurrence of SIDs, the observational data of the full solar flare emission spectrum is required. However, the spectral observations of EUV and X-ray emissions, which are considered to significantly contribute to SIDs, are limited.

X-ray emission has been continuously observed since 1974 by the X-ray Sensors (XRS) on board the Geostationary Operational Environmental Satellite (GOES). GOES/XRS observes two wavelength bands, 0.5 to 4 Å (GOES XRS-A) and 1 to 8 Å (GOES XRS-B) (Bornmann et al. 1996).

EUV emission has been observed by different instruments because of its importance form space weather forecasting. The Solar and Heliospheric Observatory (SOHO) satellite, which launched in December 1995, has a Solar EUV Monitor (SEM) (Judge et al. 1998). This instrument has been observing EUV emissions with a 15 s time resolution since January 1996. However, SOHO/SEM only has two wavelength bands, 260 to 340 Å and 1 to 500 Å, without wavelength resolution. Hence, only the temporal variation of these EUV emissions can be known from the SOHO/SEM data. The Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite,

which launched in December 2001, has an EUV observation instrument called the Solar EUV Experiment (SEE) (Woods et al. 2005). TIMED/SEE has been observing the wavelength range of 1 to 1940 Å with a 4 Å resolution since January 2002 and has superior spectral resolution compared to SOHO/SEM. However, the time resolution of this is approximately one day, and as such, short-term fluctuations such as solar flares cannot be followed. The Solar Dynamics Observatory (SDO) satellite launched on February 2010 includes the Extreme Ultraviolet Variability Experiment (EVE) (Woods et al. 2012). The Multiple EUV Grating Spectrograph (MEGS), a subsystem of the SDO/EVE, has measured full disk solar irradiance in the 1to 1060 Å range with 1 Å spectral resolution and a 10 s time cadence since May 2010. MEGS-A observes the wavelength range 50 to 370 Å, and MEGS-B observes the wavelength range 350 to 1050 Å. MEGS-A was the only instrument that could observe throughout the day with sufficient spectral and temporal resolution to study the EUV flare emission spectra; however, this device was terminated in May 2014 owing to a charge-coupled device (CCD) power anomaly. Although MEGS-B remains in operation today, it is possible that a flare is not observed because MEGS-B can only operate for approximately three

hours a day. Therefore, the observation of high-resolution EUV emission spectra when a solar flare occur is not guaranteed.

To model the emission spectra, we must understand the emission mechanism in solar flares. The basic conceptual model for solar flares is the CSHKP model (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976; Yokoyama & Shibata 1998; Shiota et al. 2005). According to this model, solar flares are caused by “magnetic reconnection” generated in the solar corona (Innes et al. 2003; Imada et al. 2013; Warren et al. 2018). The strong magnetic tension generated by the magnetic reconnection heat accelerates the electrons or protons in the solar corona. The accelerated particles travel downward along the magnetic field lines, fall into the chromosphere, and rapidly heat the high-density plasma. The high-temperature and high-density plasmas rise from the chromosphere along the magnetic field lines and form a loop-shaped structure; this phenomenon is called “chromospheric evaporation” (Milligan & Dennis 2009; Imada et al. 2015; Lee et al. 2017). The loop structure observed by soft X-ray and EUV formed from chromospheric evaporation is called the “flare ribbon”. Soft X-ray and EUV emissions are emitted from the flare loop. The time

evaporation of the EUV emissions is characterized by the formation temperature of the emitting plasmas. A typical flare light curve of an EUV emission has as impulsive peak at the beginning, followed by a gradual peak, called the impulsive and gradual phases, respectively. In general, the relatively cooler EUV line emissions from the plasma below the transition region are observed in the impulsive phase corresponding to the rapid heating in the early stages of chromospheric evaporation, and hotter EUV line emissions are observed in the gradual phase corresponding to the radiative cooling of the flare loop. Therefore, the emission spectra are evidently different between the impulsive and gradual phases because their origins are different.

Different flare EUV emission prediction models have been constructed based on the above flare emission mechanism. The most widely used model is the Flare Irradiance Spectral Model (FISM) (Chamberlin et al. 2006, 2007, 2008). The FISM is an empirical model that derives EUV emission spectra using the GOES soft X-ray flux observation. The FISM estimates the wavelength range of 1 to 1900 Å with 10 Å spectral resolution and 60 s cadence. It has been reported that the FISM can accurately estimate the solar flare emission spectra within 40% for a wavelength in the range 140 to 1900 Å.

However, FISM has low accuracy on wavelengths less that 140 Å; this is the wavelength range containing the EUV emission lines that are mainly enhanced during the gradual phase of a flare. This is because the FISM considers the time evolution of all EUV line emissions to be the same as the time evolution of the soft X-ray during the flare, and the cooling of the flare loop (time difference of EUV line emissions) is not well represented. Consequently, the FISM underpredicts the flare duration and deposited energy (Thiemann et al. 2017).

The Q_{EUV}, for which the 0 to 450 Å EUV band is an important indicator for the EUV irradiance input to the Earth's upper atmosphere (Strickland 1995), and the EUV irradiance in the 0 to 70 Å and 70 to 170 Å bands have the greatest contribution to the Q_{EUV} (Woods et al. 2011). Therefore, EUV irradiance from wavelengths less than 140 Å is important. To solve this discrepancy, it is necessary to estimate the time evolution of the EUV emissions accurately.

Other physics-based models have been constructed for this purpose; however, the EUV emission was only partially reproduced (Li et al. 2014; Zeng et al. 2014). Thiemann et al. (2017) partially succeeded in modeling the timing to coronal loop cooling with an

empirical rule. These studies used a zero-dimensional hydrodynamic model to simulate the thermal evolution of the coronal loops, called the enthalpy-based thermal evolution of loops (EBTEL) model, that could calculate the temperature and density in the flare loop without calculating the spatial loop evolution (Klimchuk et al. 2008; Cargill et al. 2012). The EBTEL model did not calculate the spatial distribution of the emitting plasma in the flare loop; hence, it is possible that the emission from the transition region plasma would not be reproduced accurately (Kawai et al. 2020). Kawai et al. (2020) introduced a new method for reproducing EUV flare emission spectra considering the time evolution of the plasma distribution in the flare loop. This method was constructed using a one-dimensional hydrodynamic calculation and an atomic database. The details of the method are described in detail in Section 2.

In this paper, we present the statistical results of the EUV emission spectra observed by SDO/EVE for 21 flare events and compare these with the spectra reproduced by Kawai et al. (2020)'s method. The purpose of this study is to investigate the accuracy in reproducing solar flare emission spectra using a simple method based on the physics of flare loops and to examine the important parameters for reproducing the solar flare

emissions.

The remainder of the paper consists of following sections. Section 2 presents the extraction of the comparative parameters using GOES and SDO/EVE. Section 3 introduces the models used in this study. Section 4 presents an example of the derivation of the solar flare emission spectra using the proposed model. Section 5 presents the statistical results of the comparison between the proposed model simulations and observations and verifies the solar flare emission spectra. Section 6 discusses and summarizes the presented comparison results.

2. Data

2.1 Soft X-ray observation

we used the soft X-ray data observed by the GOES/XRS. Flare class and duration are typically determined with GOES XRS-B light curve observations. In this study, the flare start, peak, and end times were defined using the time derivative data of the GOES XRS-B light curve observations to not lose the impulsive and gradual phases. Furthermore, we divided the flare duration into the rise time and decay time to

investigate the flare evolution in detail. Figure 1 displays an example of determining the rise time and decay time for the M9.9-class flare on January 1, 2014. The rise time is determined by when the positive derivative value is observed continuously from the GOES XRS-B start time to the peak time. The decay time is determined by when the negative derivative value is observed continuously from the GOES XRS-B peak time to the end time.

2.2 EUV flare emission spectra observation

we examined the EUV emission spectra obtained from the SDO/EVE MEGS-A observations. For this study, we selected flare events greater than M3-class flare that occurred between November 2010 and May 2014 from the Hinode flare catalogue (Watanabe et al. 2012). We used 21 events observed by the SDO/EVE MEGS-A during this period.

Figure 2 displays the EUV spectrum at flare peak time (18:52 UT) for the M9.9-class flare on January 1, 2014 observed by the SDO/EVE MEGS-A. This EUV spectrum was subtracted from the spectral value of each wavelength before the flare as the background. We focused on the six EUV flare lines of Fe VIII 131 Å, Fe XV 284 Å, Fe

XVI 335 Å, Fe XVIII 94 Å, Fe XX 133 Å, and He II 304 Å, which were strongly enhanced during the flare. The formation temperature of the Fe XX 133 Å is ~ 9 to 13 MK, Fe XVIII 94 Å is ~ 6 MK, Fe XVI 335 Å is ~ 3 MK, Fe XV 284 Å is ~ 2 MK, Fe VIII 131 Å is ~ 0.4 MK, and He II 304 Å is ~ 0.05 MK. Figure 3 displays the EUV light curves of these six flare lines during M9.9-class flare on January 1, 2014. We subtracted 3 min, the average value, from before the flare of each line flux as the background, and used 110 s as the running average to remove the noise due to short term fluctuations (dashed line in Figure 3).

To investigate the flare deposited energy and duration, which have a significant influence on the Earth's thermosphere and ionosphere response (Qian et al. 2011), we extracted the "EUV flare time-integrated irradiance" and the "EUV flare line rise time" as comparison parameters.

The EUV flare time-integrated irradiance is the time-integrated value of the irradiance from the flare start to end time. We examined for EUV flare lines 55 to 355 Å and 55 to 135 Å band. The wavelength band of 55 to 135 Å, where the uncertainty of the FISM calculation is considerable and significantly influences the Earth's ionosphere (Woods

et al. 2011; Thiemann et al. 2017). This relatively short wavelength band consists of the hot EUV lines and dominates the EUV emissions in the gradual phase (Woods et al. 2011). The EUV flare rise time is the duration from the flare start to EUV line peak time as with the above mentioned soft X-ray observation.

3. Models

3.1 Coordinated Astronomical Numerical Software (CANS) 1D package

We used the one-dimensional hydrodynamic model called CANS 1D package (http://www-space.eps.s.u- tokyo.ac.jp/~yokoyama/etc/cans/index-e.html) to solve the physical process of the plasma in the flare loop. This package can calculate the energy redistribution process in the flare loop that occurs after the energy input. CANS 1D simulates one-dimensional fluid motion and energy transfer along an invariant magnetic loop. It assumes that the cross section of the magnetic loop does not change in time. The fluid was considered as non-viscous and compressible and included heat conduction and radiative cooling. Gravity was also considered. The fundamental equations of CANS 1D are as follows:

$$\frac{\partial}{\partial t}(\rho S) + \frac{\partial}{\partial x}(\rho V_x S) = 0\#(1)$$

$$\frac{\partial}{\partial t}(\rho V_x S) + \frac{\partial}{\partial x}[(\rho V_x^2 + p)S] = \rho g S\#(2)$$

$$\frac{\partial}{\partial t}\left[\left(\frac{p}{\gamma - 1} + \frac{1}{2}\rho V_x^2\right)S\right] + \frac{\partial}{\partial x}\left[\left(\frac{\gamma}{\gamma - 1}p + \frac{1}{2}\rho V_x^2\right)V_x S - \kappa\frac{\partial T}{\partial x}S\right] = \left(\rho g V_x + H - R + H_f\right)S\#\#\#\#$$

$$p = \frac{k_B}{m}\rho T\#(4)$$

where ρ is the plasma density, S is the cross section, V_x is the plasma velocity, g is the gravitational acceleration, $\gamma = 5/3$ is the specific heat ratio, κ is the thermal conductivity coefficient, H is the static heating, R is the radiative cooling, H_f is the flare heating term, k_B is the Boltzmann constant, and m is the mean particle mass. The Spitzer model was used as the thermal conductivity coefficient (Spitzer 1962). The calculation region is from the foot point of the flare loop, which means the photosphere ($x = 0$) to the flare loop top ($x = L$), where L is the half-loop length.

Flare heating is given as a function of time and space, as follows:

$$H_f = H_{f0} \cdot q(t) \cdot f(x)\#(5)$$

$$q(t) = \frac{1}{4}\left\{1 + \tanh\frac{t}{0.1\tau_0}\right\}\left\{1 - \tanh\frac{t - \tau_f}{0.1\tau_0}\right\}\#(6)$$

$$f(x) = \frac{1}{\sqrt{2\pi}}\exp\left[\frac{(x - L)^2}{2w_f^2}\right] \cdot \frac{1}{2}\left\{1 + \tanh\left(\frac{x - 20\mathcal{H}_0}{3\mathcal{H}_0}\right)\right\}\#(7)$$

where H_{f0} is the input energy, τ_f is the heating duration, and w_f is the heating width. $\mathcal{H}_0$ is the scale height at the photosphere ($x = 0$).

3.2 CHIANTI atomic database

We used the CHIANTI atomic database to reproduce the X-ray and EUV emissions originating from the flare loop. The CHIANTI database contains a large amount of atomic data for the analysis of astrophysical spectra including atomic energy levels, wavelengths, radiative transition probabilities, rate coefficients for ionization, and data to calculate different emissions (Dere et al. 1997).

4. Validation of M9.9-class flare on January 1, 2014

We compared the EUV flare time-integrated irradiance and EUV flare line rise time obtained from the proposed model and SDO/EVE MEGS-A observations. The model simulations were in accordance with Kawai et al. (2020).

4.1 Preprocessing

As a preparation to simplify the derivation of the EUV emission spectrum, the

rise and decay time were fit to exponential curves using the Gauss-Newton method. Figure 4 displays an example of the fit GOES XRS-B light curve for the M9.9-class flare on January 1, 2014.

4.2 Coronal loop length measurement

The flare loop length for the parameter used in CANS 1D was estimated by the observation of the separation distance of the ribbons, called ribbon distance, with the SDO/Atmospheric Imaging Assembly (AIA) (Lemen et al. 2012). We used 1600 Å images to obtain the ribbon distance immediately before the flare start. Before deriving the ribbon distance, we corrected the projection effect by rotating the flaring region to the solar center using the solar software drot_map.pro. First, we defined the flare ribbon as a region with intensities of 40 times greater than the standard deviation of the quiet region. Ribbon distance is derived as the distance between the two brightest points in the flare ribbons and is known as the $H\alpha$ (UV) kernel (Asai et al. 2003; Temmer et al. 2007). For the M9.9-class flare on January 1, 2014, as indicated in Figure 5, the ribbon distance was derived as 23.3 arcsec. Therefore, the ribbon distance of this event was

estimated to be 16.9 Mm. Subsequently, the loop length was estimated to be 26.5 Mm by assuming a semicircle whose diameter was this ribbon distance.

4.3 Numerical simulation

We reproduced the time evolution of the plasma in the flare loop with CANS 1D as described in Section 3.1. Figure 6 displays an example of the calculated results of CANS 1D. In this case, we set L to 26.5 Mm, H_{f0} was 6.0 $\mathrm{erg\ cm^{-3}\ s^{-1}}$, w_f was 600 km, and τ_f was 240 s (Equations (5) - (7)). From the result, we identified the transition region to be near 0.3 Mm. In the figure, the temperature and density in the flare loop rise sharply in a couple of hundred seconds and at a height of 0.3 Mm, and the edge moves temporally. This represents the evolution of chromospheric evaporation. When flare occurs, accelerated particles fall on the chromosphere along the magnetic field lines. Consequently, the low temperature plasma in the chromosphere is rapidly heated and transported upward owing to the pressure gradient. Hence, this calculation can reproduce the time evolution of the plasma in the flare loop.

4.4 Conversion from GOES X-ray to EUV spectrum

We combined the CANS 1D result with the CHIANTI atomic database version 9.0 (Dere et al. 2019) to derive the synthetic flare emissions. Finally, we converted the synthetic flare emissions into a light curve that was comparable to the observation. Figure 7 displays the reproduced GOES XRS-B light curve by the proposed model. We performed the conversion as follows using the fit GOES XRS-B light curve as described above. First, we calculated the ratio between the GOES XRS-B observation and simulated GOES XRS-B light curve (integrated calculated value of 1 to 8 Å) for each observation time. Afterwards, we performed convolution on the simulated GOES XRS-B light curve with the observation. Subsequently, we calculated the ratio between the maximum value of the GOES XRS-B observation and maximum value of the convoluted GOES XRS-B light curve. We applied these two ratios to all simulated light curves. Finally, we derived the EUV emission spectra in all wavelengths that was comparable to the observation (see the Fig. 1 in Kawai et al. (2020)). Figure 8 displays an example of the EUV flare time-integrated spectra during the M9.9-class flare on January 1, 2014. The dashed red, blue, and solid green lines

indicate the values obtained from the proposed model, FISM, and SDO/MEGS-A observations, respectively. As indicated in Figure 8, both the proposed model and FISM reproduced the tendency of the observed values. Owing to the superior wavelength resolution, the proposed model reproduced each EUV flare line, which was not represented by the FISM. Figure 9 displays the light curves of the EUV flare lines observed by SDO/EVE MEGS-A (top panel), estimated by the proposed model (middle panel), and the FISM (bottom panel) for the M9.9-class flare on January 1, 2014. The wavelength resolution of these light curves was 10 Å, which was the same as FISM. Therefore, the wavelength of Fe VIII and Fe XX is 130 Å, Fe XV is 280 Å, Fe XVI is 330 Å, Fe XVIII is 90 Å, and He II is 300 Å as indicated in Figure 9. It is clear that the proposed model can reproduce the flux of each line based on the formation temperature. Conversely, the light curves of the FISM were virtually the same as the Fe XX observation of SDO/EVE MEGS-A, regardless of the lines or events. Table 1 presents the EUV flare time-integrated irradiance and EUV flare line rise time, observed by SDO/EVE MEGS-A and calculated by the proposed model for the M9.9-class

flare on January 1, 2014, respectively.

5. Statistical study for comparison between model and observation

We compared the EUV flare time-integrated irradiance and EUV flare line rise time obtained from the proposed model and SDO/EVE MEGS-A observation for 21 flare events using the same method as the event analysis in Section 4. In this study, we used the default parameter values set in CANS 1D (see the CANS 1D documentation). Afterwards, we set the optimal input energy for each flare event as a variable parameter (see the equations (5) - (7)). The GOES classes, flare dates, times, half-loop length estimations from the SDO/AIA observation, and the input energy used in the proposed model for 21 flare events are presented in Table 2.

First, we compared the flare time-integrated irradiance of each EUV line. Figure 10 displays the correlation of the EUV flare time-integrated irradiance of six flare lines. All Fe lines have acceptable correlation with the observations. However, the He II indicates poor correlation with the correlation coefficient of

0.24 (Figure 10f). As indicated in the regression lines in Figure 10, the Fe XVIII (Figure 10d) effectively reproduced the observed data. Fe XV (Figure 10b) and Fe XVI (Figure 10c) tended to be overestimated; the Fe VIII (Figure 10a), Fe XX (Figure 10e), and He II (Figure 10f) lines tended to be underestimated by the proposed model.

Afterwards, we compared the flare energies for two wavelength bands. Figure 11 displays the comparison results of the EUV flare time-integrated irradiance of two wavelength bands of 55 to 355 Å (Figure 11a) and 55 to 135 Å (Figure 11b). The results of the proposed model and FISM are plotted in red and blue, respectively. As indicated in Figure 11a, the 55 to 355 Å band was well reproduced by both the proposed model and FISM. The slopes of the regression lines were 0.81 ± 0.08 and 1.22 ± 0.02, respectively, and the correlation coefficients were 0.92 and 0.99, respectively. Moreover, for the 55 to 135 Å band, the proposed model could reproduce the observations better than the FISM (Figure 11b). From Figure 11b, the slope of the regression line for the proposed model was 0.91 ± 0.08, and the correlation coefficient was 0.94. Conversely, the

slope of the regression line for the FISM was 0.53±0.01, and the correlation coefficient is 0.99. From these results, the FISM tended to underestimate the EUV flare time-integrated irradiance at this relatively shorter wavelength band.

Figure 12 displays the comparison results of the EUV flare line rise time statistically. The correlation coefficient of the Fe VIII was 0.95 (Figure 12a), Fe XV was 0.86 (Figure 12b), Fe XVI was 0.90 (Figure 12c), Fe XVIII was 0.92 (Figure 12d), Fe XX was 0.94 (Figure 12e), and He II was 0.80 (Figure 12f). It can be clearly observed that all Fe lines indicated acceptable correlations with the observations. From these scatter plots, the calculated rise time of Fe XV, Fe XVI, and Fe XX tended to be less than the observations (Figure 12b, c, e), whereas He II tended to be greater than the observations (Figure 12f).

6. Discussion and summary

We attempted to reproduce EUV flare emission spectra using a simple physics-based model that simulates the time evolution of emitting plasma distribution in the flare loop. We verified the EUV flare time-integrated

irradiance and EUV flare line rise time of EUV line emissions for 21 events by comparing the calculation results of the proposed model and observed EUV spectral data.

For the flare time-integrated irradiance, the proposed model succeeded in reproducing the Fe VIII, Fe XVIII, and Fe XX lines (Figure 10a, d, e) as well as the 55 to 355 Å and 55 to 135 Å band (Figure 11a). Our results indicate that the physics-based model was effective in reproducing EUV flare irradiance for wavelengths less than 140 Å. Conversely, the proposed model overestimated the relatively longer wavelength lines, Fe XV and Fe XVI lines, emitted from relatively cooler plasmas (Figure 10b, c). Thiemann et al. (2018) reported that the peak EUV irradiance of emission lines with higher formation temperatures (> 9 MK) is proportional to the GOES XRS-B peak emission measure. Therefore, our results could imply that the EUV irradiance of the emitting plasmas with a lower formation temperature are not linearly proportional to the irradiance of the hotter emission lines or soft X-ray flux.

Regarding the EUV flare line rise time, the proposed model could derive the time

evolution of the EUV line emission by simulating the time evolution of the temperature in the flare loop. This tendency can be observed from the fact that the difference of peak time depending on the formation temperature of the emitting plasma was reproduced by the proposed model as indicated in Figure 9. The Fe XX line, which was emitted from the highest formation temperature plasma, had the shortest rise time (Figure 12d), and the He II line, which emitted from the lowest formation temperature, had the longest rise time (Figure 12f). This is because the time evolution of each EUV flare line is determined by the temperature of the emitting plasma in the proposed model.

For the He II emission line, both the time-integrated irradiance (Figure 10f) and EUV flare line rise time (Figure 12f) were poorly reproduced by the proposed model. This is because the proposed model neglected the EUV emissions from below the transition region, which is the origin of the optically thick plasmas, and hence, we did not calculate the radiation transfer. The proposed model is based primarily on the physical process following the soft X-ray emission. Therefore, a future work is to construct a model that can accurately reproduce the

EUV emission from optically thick plasmas that are dominant in the impulsive phase.

In this study, we used, for the most part, the default parameter values set in the CANS 1D (see the CANS 1D documentation). Then, we used the half-loop length estimated from observation, and set the optimal input energy for each flare event as a variable parameter. These parameters are listed in Table 2. Our results indicate that the EUV emissions from emitting plasma with relatively high formation temperature could be reproduced using only the flare input energy as a variable parameter.

As mentioned above, our results indicate that the physics-based model is effective for reproducing EUV flare emissions. The proposed model succeeded in reproducing not only the EUV emission intensity of Fe lines with high formation temperature but also the time evolution of all Fe lines during a flare. Because the Earth's ionosphere and thermosphere are sensitive to EUV emissions from the Sun (Qian et al. 2011), an accurate estimation of the EUV irradiance and duration during solar flares is important from the viewpoint of space weather.

Therefore, we consider that the simple model used in this study can contribute to the space weather forecast operation.

Declarations

Ethics approval and consent to participate

No applicable

Consent for publication

No applicable

List of abbreviations

AIA: Atmospheric Imaging Assembly

CANS: Coordinated Astronomical Numerical Software

CC: Correlation Coefficient

CCD: Charge-Coupled Device

EBTEL: Enthalpy-Based Thermal Evolution of Loops

EUV: Extreme Ultraviolet

EVE: Extreme Ultraviolet Variability Experiment

FISM: Flare Irradiance Spectral Model

GOES: Geostationary Operational Environmental Satellite

MEGS: Multiple EUV Grating Spectrograph

SEE: Solar EUV Experiment

SEM: Solar EUV Monitor

SDO: Solar Dynamics Observatory

SIDs: Sudden Ionospheric Disturbances

SOHO: Solar and Heliospheric Observatory

TIMED: Thermosphere Ionosphere Mesosphere Energetics and Dynamics

UV: ultraviolet

UT: universal time

XRS: X-ray Sensors

Availability of data and materials

The SDO/EVE level 2 data version 6 data are available at

http://lasp.colorado.edu/eve/data_access/eve_data/products/level2/. FISM data are available at https://lasp.colorado.edu/lisird/data/fism_flare_hr/. The flare event data used in this study can be found in Hinode flare catalogue (https://hinode.isee.nagoya-u.ac.jp/flare_catalogue/).

Competing interests

The authors declare that they have no competing interests.

Funding

Part of this work was conducted by the joint research program of the Institute for Space-Earth Environmental Research (ISEE), Nagoya University. This study was supported by JSPS KAKENHI Grant Numbers JP16H01187, and JP18H04452.

Authors' contributions

SN performed statistical study for solar flare spectrum data and drafted the manuscript. KW, TK, SI and TK discussed the results and edited the manuscript. All authors read and approved the final manuscript.

Acknowledgements

The authors would like to thank to K. Ichimoto, S. Takasao, S. Toriumi, H. P. Warren, and J. W. Reep for stimulating fruitful discussions.

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Figure legends Table Legends

Figure 1. Example of GOES XRS-B observation.

The light curve of soft X-ray flux (1 to 8 Å) observed by the GOES XRS-B for the M9.9-class flare on January 1, 2014 (upper panel). The light curve of the soft X-ray time derivative flux (lower panel). The vertical dotted, solid, and dashed lines indicate the flare start time, peak time, and end time, respectively.

Figure 2. Example of EUV spectrum observation.

The EUV spectrum at the GOES XRS-B peak time (18:52 UT) observed by the SDO/EVE MEGS-A for the M9.9-class flare on January 1, 2014. This EUV spectrum is subtracted from the value of each wavelength before the flare as the background. The

EUV flare lines focused on in this study are indicated as the vertical dotted lines.

Figure 3. Examples of EUV flare line light curves.

The light curves of each EUV flare line (Fe VIII, Fe XV, Fe XVI, Fe XVIII, Fe XX, and He II from the top to bottom panels) observed by the SDO/EVE MEGS-A for the M9.9-class flare on January 1, 2014. The solid lines indicate the observed values with 10 s cadence. The dotted lines indicate the 110 s running average values of the observed data. The 3 min average values before the flare are subtracted from each light curve as background. The vertical dotted, solid, and dashed lines indicate the flare start time, peak time, and end time, respectively. The arrows indicate the peak time for each EUV flare line.

Figure 4. Example of fit GOES XRS-B light curve for the M9.9-class flare on January 1, 2014.

The observed (red) and fit (green) light curves during the M9.9-class flare on January 1, 2014 using the Gauss-Newton method.

Figure 5. Example of flare ribbon observation.

The flare ribbon observation by the SDO/AIA 1600 Å for the M9.9-class flare on January 1, 2014. The yellow contour indicates the region with an intensity 40 times greater than the standard deviation of the quiet region. The red arrow indicates the ribbon distance defined in this study.

Figure 6. Calculated results of CANS 1D.

The hydrodynamic calculation results with CANS 1D for (a) temperature distribution, (b) density, (c) pressure, and (d) plasma velocity along the loop. The time evolution is represented by the change of the line color from blue to red.

Figure 7. Observed and reproduced light curves of GOES XRS-A and XRS-B.

The dashed and solid lines indicate the reproduced and observed light curve of GOES XRS during the M9.9-class flare on January 1, 2014, respectively. The red and blue lines represent GOES XRS-B and XRS-A, respectively.

Figure 8. Example of EUV time-integrated spectra during flare.

The EUV time-integrated spectra during the flare for the M9.9-class flare on January 1, 2014. The dashed red, blue, and solid green lines indicate the calculated spectra of the proposed model, FISM, and observed spectra by SDO/EVE MEGS-A, respectively. The wavelength resolution for FISM is 10 Å; the proposed model and SDO/EVE MEGS-A observation is 1 Å. The arrows indicate the EUV lines focused on in this study.

Figure 9. Example of EUV flare line light curves.

The EUV flare line light curves for the M9.9-class flare on January 1, 2014. The wavelength resolution of the light curves is 10 Å, which is the same as FISM. The panels indicate the light curves of Fe VIII and Fe XX 130 Å (red), Fe XV 280 Å (cyan), Fe XVI 330 Å (purple), Fe XVIII 90 Å (orange), and He II 300 Å (blue) obtained by the SDO/EVE MEGS-A observation (top panel: solid line), the proposed model estimation (middle panel: dashed line), and FISM estimations (bottom panel: dotted line), respectively. The slope of regression and correlation coefficient (CC) for each model

are shown at the upper left and bottom right.

Figure 10. Comparison results of EUV flare line time-integrated irradiance. The relationship between the SDO/EVE MEGS-A observations and the proposed model estimations of the EUV flare time-integrated irradiance for (a) Fe VIII, (b) Fe XV, (c) Fe XVI, (d) Fe XVIII, (e) Fe XX, and (f) He II. In each panel, the solid line indicates the regression of each plot; the dashed line indicates the straight line with slope of “1”. The slope of regression and correlation coefficient (CC) are shown at the bottom right.

Figure 11. Comparison results of EUV flare band time-integrated irradiance. The relationship between the SDO/EVE MEGS-A observations and proposed model estimations of the EUV flare energies of two wavelength bands for (a) 55 to 355 Å and (b) 55 to 135 Å. The results of the proposed model are plotted in red; FISM results are plotted in blue. In each panel, the solid line indicates the regression of each plot; the dashed line indicates the straight line with slope of “1”, the slope of regression is shown at the upper left and bottom right.

Figure 12. The comparison results of the EUV flare line rise time.

The relationship between the SDO/EVE MEGS-A observations and proposed model estimations of the EUV flare line rise time for the (a) Fe VIII, (b) Fe XV, (c) Fe XVI, (d) Fe XVIII, (e) Fe XX, (f) He II. In each panel, the dashed line indicates the straight line with slope of "1", the correlation coefficient (CC) is shown at the bottom right.

Table 1. Comparative parameters for the M9.9-class flare on January 1, 2014.

Table 2. Flare event list for this study.