Revisiting the Spectral Features of Ellerman Bombs and UV Bursts. I. Radiative Hydrodynamic Simulations

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Abstract

Ellerman bombs (EBs) and UV bursts are both small-scale solar activities that occur in active regions. They are now believed to form at different heights in the lower atmosphere. In this paper, we use one-dimensional radiative hydrodynamic simulations to calculate various line profiles in response to heating in different atmospheric layers. We confirm that heating in the upper photosphere to the lower chromosphere can generate spectral features of typical EBs, while heating in the mid to upper chromosphere can generate spectral features of typical UV bursts. The intensity evolution of the Hα line wing in EBs shows a rise–plateau pattern, while that of the Si IV 1403 Å line center in UV bursts shows a rise–fall pattern. However, the predicted enhancement of the FUV continuum near 1400 Å for EBs is rarely reported and requires further observations to check it. With two heating sources or an extended heating source in the atmosphere, both EB and UV burst features could be reproduced simultaneously.

Unified Astronomy Thesaurus concepts: Solar activity (1475); Solar photosphere (1518); Solar chromosphere (1479); Radiative transfer simulations (1697)

1. Introduction

Solar active regions host the majority of solar activities. Besides the large-scale energetic activities like solar flares and coronal mass ejections, many small-scale activities have also been observed. Ellerman bombs (EBs), which were first observed by Ellerman (1917), with typical features of enhanced Hα line wings and an undisturbed line center, are one of them. Subsequent observations showed that EBs are also visible in many other spectral lines or continua, including the line wings of the Ca II 8542 Å line (Fang et al. 2006; Vissers et al. 2013; Yang et al. 2013), the Ca II H and K lines (Matsumoto et al. 2008b; Rezaei & Beck 2015), the He I D3 and 10830 Å lines (Libbrecht et al. 2017), and the Mg II triplet lines (Vissers et al. 2015; Hansteen et al. 2017; Hong et al. 2017b), as well as the G band (Herlender & Berlicki 2011; Nelson et al. 2013b) and ultraviolet continua at 1600 and 1700 Å (Vissers et al. 2013; Rezaei & Beck 2015; Tian et al. 2016; Chen et al. 2017). Yet EBs are invisible in neutral metal lines (Rutten et al. 2015) and coronal lines (Vissers et al. 2013; Tian et al. 2016).

Because the visibility of EBs varies in different wavelengths, one can deduce the origin height of EBs from various spectral lines with different formation heights. Ellerman (1917) suggested that EBs must occur somewhere lower than the reversing layer of the solar atmosphere because the Hα line center is not disturbed. Nonlocal thermodynamic equilibrium models indicated that in order to reproduce the observed EB line profile, there must be heating in the lower atmosphere (near the temperature minimum region, TMR), and the local temperature enhancement is around 600–3000 K (Fang et al. 2006; Berlicki & Heinzel 2014). Recent 1D radiative hydrodynamic (RHD) models obtained similar results (Hong et al. 2017a; Reid et al. 2017). The total energy of EBs is calculated to be in the range of 1027–1029 erg (Georgoulis et al. 2002; Fang et al. 2006; Nelson et al. 2013a; Reid et al. 2016).

It seems that a consensus has been reached about the EB models when the first report of “hot explosions,” now more commonly referred to as UV bursts, have very strong and wide Si IV line profiles with superposed absorptive metal lines (Ni II and Fe II). To explain these spectral features, Peter et al. (2014) proposed that these activities are rooted in the deep atmosphere, and the expanding hot plasma due to magnetic reconnection gives rise to the Si IV line, while the less disturbed chromospheric plasma causes the metal absorption lines. Further observations showed that some UV bursts and EBs have a cospatial and simultaneous appearance (Kim et al. 2015; Vissers et al. 2015; Tian et al. 2016), which has led to the direct impression that EBs and UV bursts are possibly the same activities. This would pose a big challenge to the traditional EB model because the response in the Si IV line requires a local temperature of at least the order of 105 K. Although magnetohydrodynamic (MHD) simulations have proven that even in the partially ionized photosphere it is still possible to reach such a high temperature (Ni et al. 2016), there were still voices against it, claiming that such a high temperature below the chromosphere would destroy the typical features of an EB in the Hα line wing (Fang et al. 2017; Hong et al. 2017a). One-dimensional RHD simulations also showed that it is impossible to reproduce the spectral features of EBs and UV bursts with only one heating layer in the lower atmosphere (Reid et al. 2017).

More recent 3D RMHD simulations suggested that EBs and UV bursts are actually formed at different heights, and the formation height of the UV bursts is rendered to be within the mid to upper chromosphere (Hansteen et al. 2017, 2019). The synthetic line profiles in those simulations have reproduced some typical features of the observed ones, including the Ni II absorption line, which is explained as a contribution from the slow-rising cool dense gas between the heated chromospheric layer and the transition region (Hansteen et al. 2019). Near-limb observations also suggest that UV bursts are formed higher than EBs (Chen et al. 2019). The observation of a UV burst without any EB features showed that the Hα line center sight (Peter et al. 2014). These “hot explosions,” now more commonly referred to as UV bursts, have very strong and wide Si IV line profiles with superposed absorptive metal lines (Ni II and Fe II). To explain these spectral features, Peter et al. (2014) proposed that these activities are rooted in the deep atmosphere, and the expanding hot plasma due to magnetic reconnection gives rise to the Si IV line, while the less disturbed chromospheric plasma causes the metal absorption lines. Further observations showed that some UV bursts and EBs have a cospatial and simultaneous appearance (Kim et al. 2015; Vissers et al. 2015; Tian et al. 2016), which has led to the direct impression that EBs and UV bursts are possibly the same activities. This would pose a big challenge to the traditional EB model because the response in the Si IV line requires a local temperature of at least the order of 105 K. Although magnetohydrodynamic (MHD) simulations have proven that even in the partially ionized photosphere it is still possible to reach such a high temperature (Ni et al. 2016), there were still voices against it, claiming that such a high temperature below the chromosphere would destroy the typical features of an EB in the Hα line wing (Fang et al. 2017; Hong et al. 2017a). One-dimensional RHD simulations also showed that it is impossible to reproduce the spectral features of EBs and UV bursts with only one heating layer in the lower atmosphere (Reid et al. 2017).

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可以受到与 UV 爆发相关的上升流的影响（Ortiz et al. 2020）。如果 EBs 和 UV 爆发不是在同一高度形成的，那么区分 EBs 和 UV 爆发的光谱特征将非常关键，以避免任何误解，特别是在它们共同观测时。除了现实的 3D 模拟外，1D RHD 模拟仍然是探索这些事件的光谱特征的有效方法，因为它可以手动控制能量输入。这是一个合理的选择，如果只关心能量沉积的结果，而不是详细的物理过程。在本文中，我们使用 1D RHD 模型来计算对各种加热区域大气的线轮廓。然后将这些线轮廓与先前观测到的 EBs 和 UV 爆发的线轮廓进行比较，以便更好地约束它们的形成高度。

其余的论文组织如下。在第 2 节，我们简要介绍我们的方法。然后我们在第 3 节展示我们的主要结果。第 4 节讨论我们的结果与其他模拟和观测的比较，第 5 节是结论。

2. 方法

我们使用 1D RHD 代码 RADYN (Carlsson & Stein 1992, 1995, 1997, 2002) 来模拟 EBs 和 UV 爆发。RADYN 可以解决流体动力学方程、人口率方程和辐射传输方程，这在 10 Mm 的四分之一圆环中是隐含地与一个自适应网格结合在一起的。初始大气是安静的太阳模型（Hong et al. 2017a），基于 VAL3C 模型（Vernazza et al. 1981），具有 1 MK 的顶圈温度。根据 Hong et al. (2017a)，EBs 和 UV 爆发的加热率是加热率随高度变化的额外项。我们假设加热率是常数，并且具有高斯形状沿高度。加热率的峰值 (Q_{peak}) 设置为 500 erg cm^{-3} s^{-1} EBs 和 10 erg cm^{-3} s^{-1} UV 爆发。加热文件的宽度（定义为 1/e 最大值的一半）分别设置为 50 km EBs 和 20 km UV 爆发。加热文件的中心分别位于 300 到 600 km EBs，而 UV 爆发则位于上光球到下色球范围，从 1.5 到 1.8 Mm。图 1 显示了每种情况下的加热率的时间分布。EBs 加热率与 Reid et al. (2017) 和 Hong et al. (2017a) 相似。我们进一步讨论加热参数的选择。RADYN 包含非平衡电离（NEI）效应，而假定 Lyman 系列具有高斯形状来模拟频移重分布（PRD）效应。这是一个合理的近似（Leenaarts et al. 2012），我们直接从 RADYN 取 Hα 线轮廓。

Figure 1. The height distribution of temperature at \( t = 0 \) s (solid), as well as the heating rate in each EB (dashed and dashed–dotted) and UV burst (dotted) case.
For the Si IV lines that are not included in the main run of RADYN, we use MS_RADYN to rerun the whole simulation with the silicon atom, where we follow the main run step by step and solve the radiative transfer of the new atom (Kerr et al. 2019b). The results from MS_RADYN are then imported to RH (Uitenbroek 2001; Pereira & Uitenbroek 2015) for better

Figure 2. Time evolution of the height distributions of temperature and velocity for the EB cases, as well as the emergent line intensities. Positive velocity values denote upward motions, while negative velocity values denote downward motions. The horizontal axes of the line profile panels are in the Doppler scale.
treatment of the Si I continuum near the Si IV lines. Similar to Hong et al. (2019), in RH we stop to solve the statistical equilibrium equation for Si in order to keep the NEI effect that is present in MS_RADYN.

For the Mg II lines that are largely affected by PRD, we again use RH. Here we need to solve the statistical equilibrium equation for Mg because the level populations are not known. The NEI effects for this atom are thus absent but we try to mitigate this by including the hydrogen and electron density from RADYN (Kerr et al. 2019a; Hong et al. 2020).

3. Results

3.1. The EB Cases

In Figure 2 we show the time evolution of the height distributions of temperature and velocity for the EB cases (see the top two panels). As expected, local heating increases the temperature, and the resulting pressure gradient pushes plasma both upwards and downwards, forming bidirectional mass flows. The magnitude of heating in the four cases is the same, while the temperature enhancement and the velocity are
different from case to case, which is the largest in EB4, but the smallest in EB1. At the end of heating, the temperature of EB1 reaches 5300 K (with a temperature enhancement \( \Delta T = 700 \) K), while the temperature of EB4 exceeds 7000 K (with a temperature enhancement \( \Delta T = 2400 \) K) (Figure 3). This is because EB4 is formed in the lower chromosphere, the density of which is smaller than that of the upper photosphere where EB1 is formed. The temperature enhancements in our EB cases are within the range of the classic EB models (Fang et al. 2006; Berlicki & Heinzel 2014). The mass flow velocity, in general, is very small and does not exceed 2 km s\(^{-1}\).

The time evolution of the line intensities is also shown in Figure 2. Specifically, we plot the line profiles at 0 and 10 s in Figure 3. Generally speaking, for EB2 to EB4, one can see clear enhancements in the line intensities when time proceeds. For EB1, however, the enhancements are very faint.

All four EB cases present an enhancement in the \( \text{H}\alpha \) line wing (Figures 2 and 3(e)), which is a typical observational feature of EBs. However, the magnitude of the line-wing enhancement varies with cases—the relative increase is 20% for EB1 and can reach 110% for EB4. For EB2 to EB4, the line wings show two obvious peaks, while for EB1, the shape of the line wing is flat without any obvious peak. The \( \text{H}\alpha \) line center is also enhanced in these EB cases, with a relative increase of 10% for EB1 and 60% for EB4. The increase in the \( \text{H}\alpha \) line-core intensity is not considered as an EB feature, and most observations show an undisturbed \( \text{H}\alpha \) line core. However, there are indeed some observations that report a relative increase of up to 60% in the \( \text{H}\alpha \) line center (Vissers et al. 2013; Grubecka et al. 2016).

The most evident feature in the response of the Si IV line is the enhancement of the whole line including the FUV continuum (Figures 2 and 3(d)). In Figure 4 we show the time evolution of the FUV continuum intensity. For EB1, there is very little enhancement, while for EB2 to EB4, a sharp increase is present. The intensity can rise by more than two orders of magnitude in EB4.

In Figure 5 we plot the contribution function at the Si IV 1403 Å line center. The intensity of the Si IV line actually consists of radiation from both the FUV continuum and the optically thin spectral line. The FUV continuum, mainly contributed by Si I bound–free transitions, is formed in the lower chromosphere. Thus, heating in the lower chromosphere (EB2 to EB4) can contribute to the FUV continuum, while heating in the photosphere (EB1) has little contribution. The optically thin line, however, is formed in the transition region, where EB heating has little influence. Therefore, the enhancement of the Si IV 1403 Å line here is merely a result of the FUV continuum enhancement.

The Mg II 2791 Å line shows enhancement in the line wing and the nearby NUV continuum (Figures 2 and 3(e)). Similar to the response of the \( \text{H}\alpha \) line, the line wing of the Mg II 2791 Å line is flat for EB1, while two obvious peaks exist for EB2 to EB4. The two peaks display a weak asymmetry that originates from mass flows driven by the pressure gradient. In addition, the line center is also enhanced.

The contribution functions of the Mg II 2791 Å line center, the near wing, and the nearby NUV continuum are plotted in Figure 6. In the pre-EB atmosphere, the line center is formed in the mid-chromosphere at around 1.2 Mm, and the near wing and the NUV continuum are formed in the photosphere. When heating sets in, the opacity is increased, and the \( \tau = 1 \) height of the near wing is levitated. The heated region now has a large contribution to the near wing intensity and the NUV continuum, and the contribution function shows a second peak near the heated region. The spectral response of this line resembles that of the \( \text{H}\alpha \) line very much.

The Mg II \( k_3 \) core and \( k_2 \) peaks are formed in the mid to upper chromosphere, and thus they do not show any response to EB heating. The outer wings, however, can be enhanced because they form lower than the \( k_2 \) peaks (Figures 2 and 3(f)). Therefore, deep photospheric heating (EB1) has little contribution to the line-wing intensity. However, when the heating region moves higher (from EB2 to EB4), one can notice a gradual enhancement in the wings of this line.

### 3.2. The UV Burst Cases

We show the time evolution of temperature, velocity, and line profiles of the UV burst cases in Figure 7. The heating of UVB1 to UVB3 is located in the upper chromosphere, while it is in the transition region for UVB4. As expected, the temperature of the heated region gets enhanced, and the pressure gradient drives bidirectional mass flows. The temperature can exceed \( 10^5 \) K and approach \( 10^6 \) K in some cases, and the flow velocity can reach nearly 20 km s\(^{-1}\).

The Si IV 1403 Å line has been used to identify UV bursts. In our simulation, after a certain time of heating, this line indeed shows an enhanced and broadened profile (Figure 7). The local temperature of the heated region is around \( 10^5 \) K when the line intensity is at its maximum. As heating proceeds, the local temperature exceeds the formation temperature of this line, and thus the line intensity begins to decrease.

In Figure 8 we show the line profiles of the four UVB cases at a specific time when the Si IV line is the strongest in each case. UVB1 to UVB3 all show a double-peaked line profile, as a result of the bidirectional flows in the chromosphere. UVB4, however, shows a single redshifted peak, corresponding to the downflow below the transition region. The hot upflow plasma is in the corona that has no contribution to this line. The nearby
FUV continuum is also slightly enhanced, but not as evident as in the EB cases.

The contribution functions of the Si IV line and nearby continuum are plotted in Figure 9. The FUV continuum is mostly formed in the lower chromosphere. However, heating in the upper chromosphere can also have some contribution, which may result in the continuum increase. The line-center intensity of UVB1 to UVB3 is contributed by three parts. The first part is from the lower to mid-chromosphere around 0.9 Mm that provides the continuum photons, and the second part is from the transition region that provides the Si IV line photons. The third part, which is also the dominant part, is from the heated chromosphere where most Si IV line photons originate. For UVB4 the latter two parts are merged into one. This line is optically thin in all UVB cases because most line photons originate in specific layers far above the $\tau = 1$ height.

Figure 5. Contribution function of the Si IV 1403 Å line center in the quiet Sun and for the EB cases at $t = 10$ s. The vertical dotted lines denote the height where $\tau = 1$. 
The Mg II k line shows large enhancements of the k2 peaks as well as k3 (Figures 7 and 8(f)). The k2 peaks are not symmetric and k3 is slightly blueshifted due to the velocity gradient in the chromosphere. The width of this line also increases. However, heating does not influence the outer wings ($\Delta \nu > \pm 30$ km s$^{-1}$). By comparison, the Mg II 2791 Å line wing and the nearby FUV continuum show no response in the four cases, although the line center can be slightly enhanced (Figures 7 and 8(e)).

We also find that the Hα line wing shows no response, but the line center is enhanced in the four cases (Figures 7 and 8(c)). For UVB1 to UVB3, the line center is blueshifted, while in UVB4, the line center is redshifted.
Figure 7. Same as Figure 2, but for the UV burst cases.
4. Discussion

In Table 1 we list the spectral features of EBs and UV bursts from our results as well as previous observations and simulations. As one can see, our simulations agree with previous studies generally, with a few exceptions. These agreements and exceptions are discussed below.

4.1. Parameter Study

Both EBs and UV bursts are believed to occur in the lower and partially ionized atmosphere, thus it would be difficult to infer how the energy is exactly deposited from observations. Inversions of line profiles, either through semiempirical models (Fang et al. 2006; Berlicki & Heinzel 2014) or non-LTE inversion codes (Vissers et al. 2019a), can deduce peaks in the temperature profiles. In order to reproduce such temperature profiles, we use a simple Gaussian function for the heating profile, with three free parameters (peak, width, and center). Judging from the above results, the heating center seems to be the most important parameter. Most optically thick lines form in a height range, and their behaviors can be quite different if different atmospheric layers are heated.

It is, however, very interesting to explore how much influence the other two parameters (peak and width) would have on the line profiles. We choose EB2 and UVB1 as reference models and vary these two parameters. We choose four values for each parameter, namely, 0.2, 0.5, 2, and 5 times the original value in the reference model, and show the results in Figures 10 and 11. For all the line profiles shown in these figures, the total energy input is the same.
It is very clear that for both EBs and UV bursts, a larger heating peak would result in a more rapid rise in the line intensities (Figures 10(a) and 11(a)). Even with the same amount of input energy, a larger enhancement is expected for a larger heating peak (Figures 10(b) and 11(b)). However, the behavior of the spectral lines in response to the heating width is quite different. For the Hα line in EBs, heating with a larger width also results in a more rapid rise in the line-wing intensity (Figure 10(c)), while after some time when the same amount of energy is deposited into the atmosphere, the line profiles do not vary much (Figure 10(d)). For the SiIV 1403 Å line in UV bursts, apart from the case with a very small heating width, heating with a smaller width would normally result in a more rapid rise in the line-center intensity (Figure 11(c)). In this region, the main dissipation terms of the input energy are radiative losses and work done by the pressure gradient. For the case with a smaller heating width, the amount of work done by the pressure gradient at the height of the heating center (1.5 Mm) would be larger, while the optically thin radiative losses are smaller due to a lower electron density. After

Figure 9. Contribution function of the Si IV 1403 Å line center (black) and the nearby FUV continuum (−0.2 Å, blue) in the quiet Sun and for the UV burst cases at \( t = 10 \) s. Note that the selected time for plotting the contribution functions is different in the four cases. The vertical axes are in logarithmic scale.
smaller widths show clear enhancement of the Si IV line

Ni et al. (2021)

subtracting these dissipation terms, it turns out that the increase in the internal energy is generally larger for the case with a smaller heating width. As for the line profiles, only cases with smaller widths show clear enhancement of the Si IV line (Figure 11(d)). This is because the Si IV line forms in a certain temperature range. For a larger heating width but a shorter heating time, one would expect no response of the Si IV line, because it takes some time to heat the atmosphere until there are enough Si IV atoms. When these two parameters are combined together, the influence of the heating peak dominates (Figures 10(e)–(f) and 11(e)–(f)).

The evolution of the line intensity shows different behavior in EBs and UV bursts, which is due to the difference in the formation height of the Hα and the Si IV line. The Hα line wing forms in the TMR where the input energy can be effectively radiated away through optically thick line photons, thus one sees a rise–plateau pattern in the lightcurve (Figure 10, left column). The Si IV line, however, forms higher where the input energy cannot be radiated away effectively, thus the local temperature rises very quickly. The number of the Si IV atoms rises first and then falls when the temperature is so high that they get ionized, thus one sees a rise–fall pattern in the lightcurve (Figure 11, left column). For each case in the EB group or UV burst group, the pattern is similar and does not depend on the heating parameters, and one would expect similar line profiles at a certain time in each case, with a different total deposited energy. In our simulations, we choose a set of heating parameters that could show typical EB and UV burst features.

4.2. The FUV Continuum Enhancement of EBs

The enhancement of the FUV continuum is the most striking feature in our EB simulations. Previous observations confirmed that EBs are visible in the FUV continuum at 1600 and 1700 Å (Vissers et al. 2013; Rezaei & Beck 2015; Tian et al. 2016; Chen et al. 2017). And it is very promising to detect EBs from these wave bands (Vissers et al. 2019b). However, there are rare reports of a significant enhancement near the 1400 Å continuum. The observed enhancement only appears in few cases and is less than one order of magnitude (Tian et al. 2016; Chen et al. 2019). Because most previous IRIS observations in the FUV wave band lack radiometric calibration, it would be difficult to directly compare the intensity values.

The FUV continua from 1400 to 1700 Å are mainly contributed by bound–free transitions of neutral metals (Simões et al. 2019) and thus their formation height should not vary much. In fact, Tian et al. (2016) showed that if the FUV continuum near 1400 Å is enhanced, then the AIA 1700 Å image is very likely to brighten up in the same region.

The FUV continuum near 1400 Å is formed in the lower chromosphere. Therefore, if heating is constrained to the deep photosphere (EB1 and EB2 in the first few seconds), then the

| Activity | Hα Wing | Hα Center | Mg II Triplet Wing | Mg II k2/λ2 Peaks | NUV Continuum | Si IV | FUV Continuum |
|----------|---------|-----------|--------------------|-------------------|---------------|-------|---------------|
| Hansteen et al. (2017) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hong et al. (2017b) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Ortiz et al. (2020) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Peter et al. (2014) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Tian et al. (2016) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hansteen et al. (2017) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Ortiz et al. (2020) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Vissers et al. (2015) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Tian et al. (2016) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Chen et al. (2019) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Ortiz et al. (2020) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hansteen et al. (2017) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Reid et al. (2017) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hong et al. (2017a) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hansteen et al. (2017) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hansteen et al. (2019) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| This paper | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hansteen et al. (2017) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Hansteen et al. (2019) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Ni et al. (2021) | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |
| This paper | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ |

Notes. Early observations without IRIS are not included in this table. The “✓” sign indicates that there is an obvious enhancement of the intensity, and the “✗” sign means that there is hardly any response. It is left blank if the wavelength is not used or it is hard to judge if there is a definite enhancement.

a By heating events unrelated to EBs.
FUV continuum has little response to it (Figure 4). Seo et al. (2019) also calculated an EB model with heating in the deep photosphere, and they were unable to reproduce enhancements in the FUV continua near 1600 and 1700 Å. These spectral features shown in our simulations are supported by some observations, such as the EB (with no association of UV bursts) reported by Ortiz et al. (2020) and the weak EB reported by Hong et al. (2017b).

However, there are still some observations of EBs that cannot fit into the above category. An example is the strong EB reported by Hong et al. (2017b), which shows clear emission peaks in the Hα line wings and an enhancement in the AIA 1700 Å emission, but no response in the IRIS SiIV 1403 Å line. This lack of enhanced FUV emission in the IRIS SII could be due to a low signal-to-noise ratio of the FUV band because the exposure time in this observation is too short. Some other events, which show a response in the AIA 1600 and 1700 Å continua but no response in the FUV continuum near the IRIS SiIV 1403 Å line, are actually EBs associated with UV bursts. In these events, the chromosphere can be heated as a result of the UV burst, and the metal lines in the FUV wave band (e.g., the CIV, SiII, and HeII lines), with formation temperatures of log \( T \approx 4.2-5.0 \) K (Simões et al. 2019), could also contribute to an enhancement in the integrated AIA 1600 and 1700 Å emission.

The FUV continuum is also enhanced during flares, and there have been many observations (Tian et al. 2014; Li et al. 2015; Warren et al. 2016; Tian & Chen 2018; Yu et al. 2020; Zhou et al. 2020). Recent RHD simulations of solar flares showed that the intensity of the FUV continuum can reach...
$3 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$ for case 5F9E20 (similar to a C-class flare) (Kerr et al. 2019b), which is similar to our EB3. We speculate that the expected increase in the FUV continuum could be detected by IRIS if the exposure time is not too short.

More observations and model simulations of EBs, especially in the FUV wavelengths, are thus needed to explore the causes for the discrepancy between observations and simulations. It would be helpful if these observed EBs are not related to UV bursts so that the different spectral features of EBs and UV bursts would not superpose.

### 4.3. The Mg II Lines of EBs

Previous observations have reported plenty of EB events with line-wing enhancement in the Mg II triplet lines (including the Mg II 2791 Å line) (Vissers et al. 2015, 2019a; Hong et al. 2017b; Ortiz et al. 2020). From simulations, we confirm that the line wings of the Mg II 2791 Å line, especially the emission peaks appearing in some cases, are formed in the heated region in the lower atmosphere (Figure 6). Hong et al. (2017b) suggested a positive relationship between the line-wing intensities of the H$\alpha$ line and the Mg II triplet lines. A further statistical study, similar to Vissers et al. (2019b), is needed in order to investigate the potential of detecting EBs using the Mg II triplet lines.

The response of the Mg II k line to EB heating has also been reported in some previous literature. However, we find that only the outer wings of Mg II k are significantly enhanced while the $k_2$ peaks show no response to EB heating. In fact, the $k_2$ peaks are only enhanced in cases of UV bursts, which is confirmed by recent observations (Ortiz et al. 2020).
4.4. The Flow Velocity and Line Asymmetries of EBs

In our simulation, the mass flow velocity that is related to an EB is very small (below 2 km s\(^{-1}\)), and it is difficult to obtain a large velocity in the absence of magnetic fields. The flow velocities that are inferred from observed line profiles, either using the bisector method or a cloud model, have typical values of below 10 km s\(^{-1}\) (Matsumoto et al. 2008a; Yang et al. 2013; Hong et al. 2014; Libbrecht et al. 2017). Recent non-LTE inversions recovered the bidirectional jets that exceed 20 km s\(^{-1}\) (Vissers et al. 2019a). MHD simulations of EBs usually show bidirectional flows from several to tens of km s\(^{-1}\) and are more comparable to observations (Isobe et al. 2007; Archontis & Hood 2009; Ni et al. 2016; Hansteen et al. 2017, 2019).

Due to the weak mass flow in our simulations, the resulted H\(\alpha\) line asymmetry is also very weak. The red asymmetry of the wing emission in the Mg II 2791 Å line is more obvious. The synthetic line profiles in our simulation of EBs only show a red asymmetry, while in observations, both red and blue asymmetries could be present (Bruzek 1972; Kitai 1983; Dara et al. 1997; Fang et al. 2006; Socas-Navarro et al. 2006; Hashimoto et al. 2010; Vissers et al. 2013). In addition, a moving overlying canopy might also influence the line asymmetry (Bruzek 1972; Kitai 1983; Watanabe et al. 2011; Rutten et al. 2013; Vissers et al. 2019b).

4.5. The Formation Height of UV Bursts

The formation height of UV bursts has undergone a long discussion. Recent studies suggest that UV bursts are formed in the mid to upper chromosphere (Hansteen et al. 2017, 2019; Chen et al. 2019). In our simulations, the cases of UVB1 to UVB3 reproduce well the spectral features that are typical of UV bursts. In particular, the synthetic Si IV and Mg II k line profiles are very similar to the observed ones. We successfully reproduce the double-peaked Si IV line profiles that have been frequently observed in previous studies (Peter et al. 2014; Vissers et al. 2015; Tian et al. 2016; Hansteen et al. 2017; Ortiz et al. 2020). The line width, however, is not comparable to observations, which is a modeling limitation and is discussed further in Section 4.7.

For the H\(\alpha\) line, we confirm that the line center can be enhanced as shown in recent simulations (Hansteen et al. 2017). We also find that in some cases (like UVB1 to UVB3), the line center is blueshifted. Similarly, Ortiz et al. (2020)
observed a blueshifted Hα line center in UV bursts, and they interpreted it as a result of an accompanying surge. The case of UVB4 shows different spectral features from the other three cases. Yet UVB4 can still be classified as a UV burst due to the enhancement in the SiIV line (Young et al. 2018). The specific features of redshifted Hα and SiIV lines have also been shown in previous observations of UV bursts (Ortiz et al. 2020).

4.6. The Coexistence of EBs and UV Bursts

EBs and UV bursts appear to be associated with each other in many events (Vissers et al. 2015; Tian et al. 2016; Chen et al. 2019; Ortiz et al. 2020), so it would be very interesting to explore possible temperature structures that could generate both features simultaneously. A previous study of line inversions suggested two separate heating sources in the atmosphere (Vissers et al. 2019a). Thus, we run a new simulation with heating in both the TMR and the upper chromosphere. The new heating function is simply a combination of the heating functions in cases EB3 and UVB1, and we show the results in Figure 12. It is quite clear that because the two heating sources are quite far apart, they do not seem to influence each other. The typical EB features that are present in case EB3, as well as the typical UV burst features that are present in case UVB1, both appear in the results here as expected (Figures 12(c)–(f)). Our results agree with previous observations (Vissers et al. 2015; Ortiz et al. 2020) to a large extent. However, how these two heating sources are physically connected to each other would need further study with MHD simulations.

Hansteen et al. (2019) showed that an extended current sheet is likely to generate both EB and UV bursts in the atmosphere. To mimic such a current sheet, we employ a Gaussian heating profile with a very large width. As shown in Figure 1, the heating profile is centered at 600 km, with a peak of 500 erg cm⁻³ s⁻¹ and a width of 500 km. The results are shown in Figure 13. In this case, there are prevailing upflows in the lower atmosphere, and all the line centers are blueshifted. Compared with the above case, all the line profiles except SiIV have similar shapes but are dramatically enhanced. The Hα line-wing intensity increases by 120%, and the line-core intensity increases by 900%. The line profile still presents an EB-like shape, with an emissive wing and an absorptive core.
and we speculate that the overlying canopy, which is absent in our model, could reduce the line-core intensity to some extent. The SiIV line is enhanced and broadened, but with a single peak because there is no downflow in the line formation region. However, in observations, we are not always observing vertically, thus EBs and UV bursts can be some distance apart in our field of view (e.g., Chen et al. 2019). We assume that the size of EBs/UV bursts is 0′′4 and bury the above column atmosphere with extended heating into a quiet-Sun background atmosphere. We then recalculate the line profiles with a viewing angle of $\mu = 0.5$ and show the results in Figure 14. When different parts of the column atmosphere are observed from the side, the line intensities can vary. The intensity of the H$\alpha$ line wing (~0.75 Å) is enhanced within the height range of 0.5–1.5 Mm of the heated atmosphere. This extended brightening is quite similar to the "flame morphology" in previous studies (Vissers et al. 2015; Chen et al. 2019; Hansteen et al. 2019). There are two height ranges where the intensity of the SiIV line center is increased. The one in the lower chromosphere (around 0.6 Mm) is contributed by the FUV continuum, while that in the upper chromosphere (around 1.5 Mm) is contributed by the SiIV line. The line profiles also vary when the line of sight (LOS) reaches different parts of the heated atmosphere. At a lower height (0.6 Mm), one sees EB features that are similar to our simulation results of an isolated EB in Section 3; when the LOS gradually moves to a larger height, UV burst features begin to appear, and at 1.5 Mm, there appear to be both features.

### 4.7. Limitations

In our simulations, we are unable to reproduce very broad Mg II and Si IV line profiles as in the observations. Such a discrepancy originates from the limitations of our 1D RHD modeling. Because we do not consider magnetic fields, the heating rate, as a result of magnetic reconnections in the lower atmosphere, is manually set as a simple Gaussian function, which might differ from the real situation. Thus, the heating rate might be underestimated at certain heights, where one also

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**Figure 14.** Line intensities and profiles at different heights with a viewing angle $\mu = 0.5$ for a case with extended heating in the atmosphere. (a) Line intensities of the H$\alpha$ line center (dashed) and blue wing (~0.75 Å, solid) at different heights. (b) Line intensities of the Si IV 1403 Å line center at different heights. (c)-(f) Line profiles at selected heights, which are marked with colored vertical lines in panels (a) and (b). Black lines denote quiet-Sun profiles.
underestimates the electron density that could contribute to a wider line wing (Rubio da Costa & Kleint 2017; Zhu et al. 2019). The nonthermal broadening due to mass flows and turbulence is also underestimated because of the lack of reconnection details.

The 1D nature of our simulations implies that the intensities at line centers might be overestimated, because the 3D radiative transfer effect could smear out some portion of the emission (Leenaarts et al. 2012, 2013). In addition, the atmosphere used in our simulations is an averaged atmosphere for the quiet Sun. In reality, due to the complexity of the magnetic fields in the active region, the atmospheric structure could also be very complicated. For example, in our simulations, the enhancement of the Hα line-center intensity in EB cases could be due to the absence of a fibrillar canopy in the chromosphere that can lead to a strong absorption (Hong et al. 2014; Hansteen et al. 2017; Vissers et al. 2019a).

5. Conclusion

In this paper, we explore the responses of various spectral lines and continua toward heating in different atmospheric layers. Generally speaking, we successfully reproduce the spectral features of typical EBs and UV bursts, respectively. Our main results, along with previous observations and simulations, are listed in Table 1 and can be summarized as follows.

1. Heating in the lower atmosphere can generate typical EB features. The evolution of the Hα line-wing intensity shows a rise–plateau pattern. Enhancement in the FUV continuum near 1400 Å is predicted if heating extends above the TMR. The FUV continuum intensity of EB3 can reach $3.4 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, which is similar to the case of a C-class flare (Kerr et al. 2019b).

2. Heating in the mid to upper chromosphere can generate typical UV burst features. The evolution of the Si IV 1403 Å line-center intensity shows a rise–fall pattern. At a certain time, the Si IV 1403 Å line is enhanced and very broad, with two emission peaks corresponding to the associated bidirectional mass flows. The Hα line center is also blueshifted as a result of the upflow.

3. Heating in the transition region would result in redshifted Si IV and Hα lines.

4. Heating with two sources in the atmosphere, or an extended source, could reproduce both EB and UV burst features simultaneously.

Most of our calculated spectral features agree with previous observations and simulations with only a few exceptions. The predicted enhancement of the FUV continuum near 1400 Å in EB cases is rarely observed, although there are frequent reports of brightenings in AIA 1600 and 1700 Å images. We speculate that these EBs might originate from the deep photosphere, or the signal-to-noise ratio of the IRIS FUV observations is too low. It is also possible that in some reported EBs, the AIA image 1600 and 1700 Å emissions could be influenced by a related UV burst, where the chromospheric metal lines are enhanced and increase the integrated FUV emissions in the wave band. In addition, our simulations show an enhancement of the Hα line center during EBs and relatively narrow Mg II and Si IV lines that are incomparable to most observations. These are due to the limitations of our 1D RHD simulations.

There have been observations of EBs in 1400, 1600, and 1700 Å images (Vissers et al. 2015; Tian et al. 2016; Chen et al. 2017; Ortiz et al. 2020), yet we still expect more to statistically check the visibility in all these three FUV bands, with a particular combination of IRIS and AIA observations. The response of the Hα line in UV bursts (Hansteen et al. 2017; Ortiz et al. 2020) is also an interesting topic for future observations. In addition, joint observations including other chromospheric lines like the He I D3 and 10830 Å lines (Libbrecht et al. 2017), are useful to restrict the physical models. On the other hand, 3D (RM)MHD modeling is needed to take into account the complexity of the atmosphere and magnetic field structure, which can include the 3D effects that are missed in the 1D models. Besides the realistic 3D simulations (Hansteen et al. 2017, 2019), it would also be helpful to perform some simplified 3D experiments with different predefined magnetic structures, in order to explore the formation mechanism of these events.

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17
