

Formation height of ultraviolet C I and C IV spectral lines during solar flares

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Abstract. Imagens solares obtidas em 1600 Å e 1700 Å pelo Atmospheric Imaging Assembly (AIA) têm revelado a morfologia e a evolução de ribbons de flares solares em grande detalhe. Apresentamos a análise preliminar da estrutura de altura de um caso raro de um flare ribbon observado no limbo solar. A intensidade dos perfis radiais ao longo do ribbon foram ajustados com uma função gaussiana para estimar a altura da emissão em ambas as bandas UV, e encontramos que a diferença média de altura entre as duas bandas UV é de 0.67 ± 0.19 Mm. A análise foi complementada pelo cálculo da altura de formação das principais contribuições espectrais para as imagens UV do AIA para a emissão da erupção: o duplete C IV 1550 Å para 1600 Å e a linha C I 1656 Å para 1700 Å. Os resultados das simulações estão, em geral, de acordo com a análise observacional.

Resumo. Solar images taken at 1600 Å and 1700 Å by the Atmospheric Imaging Assembly (AIA) have revealed the morphology and evolution of flare ribbons in great detail. We present the preliminary analysis of the height structure of a rare case of a flare ribbon observed at the solar limb. The intensity of radial profiles across the flaring ribbons were fitted with a Gauss function to estimate the height of the emission in both UV bands, and found that average height difference between the two UV bands to be 0.67 ± 0.19 Mm. The analysis was complemented by calculating the formation height of the main spectral contributions for the AIA UV images for flare emission, C IV 1550 Å doublet for 1600 Å, and C I 1656 Å line for 1700 Å. The simulations results are in general agreement with the observational analysis.

Keywords. Sun: chromosphere – Sun: flares – Radiative transfer

1. Introduction

Solar flares are transient events that occur in the solar atmosphere, when large amounts of energy are suddenly released and transferred into plasma heating and particle acceleration. A fraction of this energy is transported by accelerated electrons from the corona into the chromosphere, where the energy is deposited and dissipated (Fletcher et al. 2011; Holman et al. 2011). With this energy input, the structure of the chromosphere is expected to change due to the increase of the temperature and pressure of the local plasma (Allred et al. 2005). However, an observational confirmation of this is challenging due to the low chances of registering a flare close to the solar limb, where the vertical structure of the chromosphere could be observed. This has been done before but only for a few cases. Martínez Oliveros et al. (2012), using hard X-ray and continuum observations close to the limb, coupled with an accurate assessment of source position from stereoscopy, measured a flare source height of ~ 300 km above the photosphere. Similar observations but without the stereoscopic constraints placed this higher, at ~ 500 - 800 km (Krucker et al. 2015). Kuridze et al. (2020) reported observations where the source heights observed in the far wings of $H\beta$ were between 300-500 km above the limb defined in this wavelength, expected to be ~ 350 km above the photosphere. The thickness was estimated at ~ 300 km (4 times than the telescope's diffraction limit). Source thicknesses in optically-thin line wings are likely upper limits due to integration through the ribbon extended along the line-of-sight.

In this work, we present the preliminary results of the vertical structure of a flare using observations in the ultraviolet (UV) range, together with simulations to help the interpretation of the data. The solar flare event SOL2014-02-25T00:49UT was a GOES X4.9 class event which its images have been taken at 1600

Å and 1700 Å by Atmospheric Imaging Assembly (AIA) on board the Solar dynamic Observatory (SDO). Simões et al. (2019) have shown that the flare excess emission from AIA 1600 Å has a large contribution from the C IV 1550 Å doublet (26%), while AIA 1700 Å samples C I 1656 Å line (38%). Using this information, in this work we apply radiative transfer framework Lightweaver (Osborne et al. 2019) together with radiative hydrodynamic models of solar atmosphere, from F-CHROMA RADYN database (Carlsson et al. 2023), in order to simulate flare condition in terms of plasma temperature and electron density, and identify the formation height of C I and C IV spectral lines.

2. Data analysis

The event reported is SOL2014-02-25T00:49, a GOES X4.9 class event in active region AR 11990. It is a unique observation of a solar flare that occurred at the limb using AIA and Extreme Ultraviolet Imager (EUVI) on the Solar-Terrestrial Relations Observatory B spacecraft (STEREO/EUVI B) used to confirm the limb location of the ribbon.

Images were selected at 00:47:52 UT (1600 Å) and 00:48:07 UT (1700 Å) at which time the limb ribbons are well-defined and extended. Radial cuts were made, numbered 1-40, taken through the ribbon and the corresponding intensity profiles, as shown in left panel in Figure 1. To visualize the real profile of the flare excess emission they take every profile and then subtract the pre-flare profile. A Gaussian fit was made to obtain the radial distance (height) of the vertical profile. Taking one of the radial cuts (shown in right-hand panels in Figure 1), the heights of the emission above the photosphere are 1.83 Mm at 1600 Å and 1.16 Mm at 1700 Å. Repeating the procedure over the duration

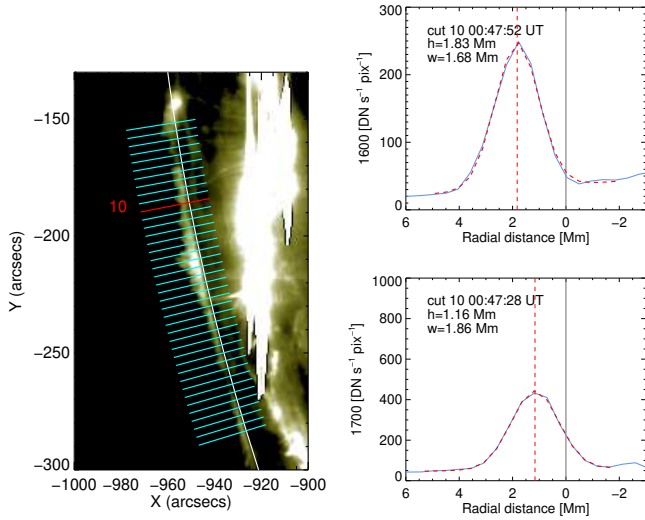


FIGURE 1. Left: Radial cuts through the solar 1600 Å image to extract the brightness structure of the flare ribbons. Right: background-subtracted intensity profiles along cut 10, for 1600 Å (top) and 1700 Å (bottom), fitted with a Gaussian function (red) to determine the centroid of the emission.

of the flare, we find a statistically significant offset in centroid positions of 0.67 ± 0.19 Mm.

3. Simulations

We used radiative-hydrodynamic (RHD) simulations from (Carlsson et al. 2023) together with the Lightweaver radiative transfer framework Osborne & Milić (2021) to obtain the formation heights of the emission lines of C I and C IV in a solar atmosphere under flare conditions. These lines represent the main spectral contributions to the 1700 Å and 1600 Å filters in AIA, respectively (Simões et al. 2019). We verify that the height offset between them is about 600 [Mm], around 600 km above the solar limb, which is consistent with the one observed by AIA. The simulation follows the atmospheric plasma response to an energy input from accelerated electrons. In Figure 2 we present the simulation results, showing temperature as a function of height in the atmosphere (at $t = 0$ and $t = 10$ s, during quiet and flare conditions, respectively), and the formation heights of both carbon lines (C IV in green and C I in pink) at $t = 10$ s. The height difference of the formation regions of the C lines is consistent with their formation temperatures: $T = 10^{5.05}$ and $T = 10^{4.15}$ K, for C IV and C I, respectively, and similar to the observational results of 0.67 ± 0.19 Mm.

4. Conclusion

Our simulation results showed good agreement with the observational measurements of the difference in height emission of the C I and C IV lines of 0.67 ± 0.19 Mm. These are preliminary results, and different energy input conditions may result in different heights for the line formation. By testing the formation heights under different heating scenarios, it should be possible to infer the parameters of the accelerated electrons during this flare.

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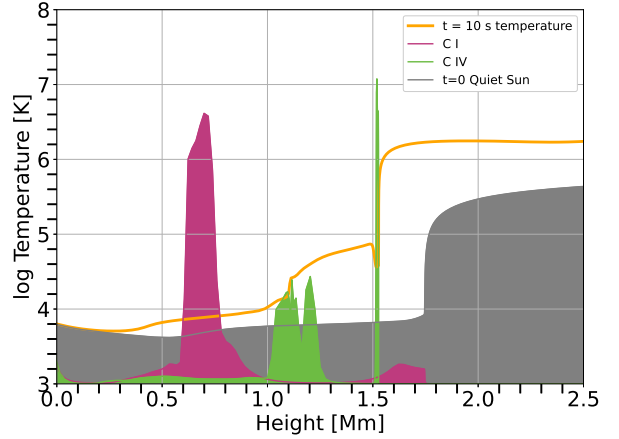


FIGURE 2. Simulated solar atmosphere model for the contributions of the C I and C IV spectral lines. The gray shaded area corresponds to the quiet Sun temperature profile, the pink region the C I contribution, the green region the C IV contribution and the profiles of temperature (orange) and electron density (red)

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