Multi-passband Observations of a Solar Flare over the HeI 10830 Å line

Yan Xu1,2, Xu Yang1,2, Graham S. Kerr3,4, Vanessa Polito5,6, Viacheslav M. Sadykov7, Ju Jing1,2, Wenda Cao1,2, and Haimin Wang1,2

1 Institute for Space Weather Sciences, New Jersey Institute of Technology, 323 Martin Luther King Blvd., Newark, NJ 07102-1982, USA
2 Big Bear Solar Observatory, New Jersey Institute of Technology, 4086 North Shore Ln., Big Bear City, CA 92314-9672, USA
3 NASA Goddard Space Flight Center, Helio-Physics Sciences Division, Code 671, 8800 Greenbelt Rd., Greenbelt, MD 20771, USA
4 Department of Physics, Catholic University of America, 620 Michigan Ave., NE, Washington, DC 20064, USA
5 Bay Area Environmental Research Institute, NASA Research Park, Moffett Field, CA 94035-0001, USA
6 Lockheed Martin Solar and Astrophysics Laboratory, Building 252, 3251 Hanover St., Palo Alto, CA 94304, USA
7 Physics & Astronomy Department, Georgia State University, 25 Park Place NE, Atlanta, GA 30303, USA

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Abstract

This study presents a C3.0 flare observed by the Big Bear Solar Observatory/Goode Solar Telescope (GST) and Interface Region Imaging Spectrograph (IRIS) on 2018 May 28 around 17:10 UT. The Near-Infrared Imaging Spectropolarimeter of GST was set to spectral imaging mode to scan five spectral positions at ±0.8, ±0.4 Å and line center of HeI 10830 Å. At the flare ribbon’s leading edge, the line is observed to undergo enhanced absorption, while the rest of the ribbon is observed to be in emission. When in emission, the contrast compared to the preflare ranges from about 30% to nearly 100% at different spectral positions. Two types of spectra, “convex” shape with higher intensity at line core and “concave” shape with higher emission in the line wings, are found at the trailing and peak flaring areas, respectively. On the ribbon front, negative contrasts, or enhanced absorption, of about ~10%–20% appear in all five wavelengths. This observation strongly suggests that the negative flares observed in He I 10830 Å with mono-filtergram previously were not caused by pure Doppler shifts of this spectral line. Instead, the enhanced absorption appears to be a consequence of flare-energy injection, namely nonthermal collisional ionization of helium caused by the precipitation of high-energy electrons, as found in our recent numerical modeling results. In addition, though not strictly simultaneous, observations of Mg II from the IRIS spacecraft, show an obvious central reversal pattern at the locations where enhanced absorption of He I 10830 Å is seen, which is consistent with previous observations.

Unified Astronomy Thesaurus concepts: Solar flares (1496); Solar activity (1475); Solar flare spectra (1982)

1. Introduction

The helium triplet around 10830 Å is among the most important diagnostics of the chromosphere. Flare observations using the He I 10830 Å line started several decades ago (Harvey & Recely 1984), however, there have not been many events observed with this line since then (You & Oertel 1992; Penn & Kuhn 1995; Li et al. 2006; Zeng et al. 2014; Xu et al. 2016; Kobanov et al. 2018). Most of the reported flares show emission similar to the observations in other chromospheric wavelengths, such as Hα. Li et al. (2007) studied spectrographic data of several flares and suspected that a certain level of nonthermal effects, such as those that might occur in mid-C-class flares, is needed for He I 10830 Å emission to reach a detectable level. With much higher spatial resolution, Zeng et al. (2014) reported emissions with more than 50% contrast in a C3.9 flare observed by Big Bear Solar Observatory (BBSO)/Goode Solar Telescope (GST).

In addition to the emission of the He I 10830 Å line, Harvey & Recely (1984) and Xu et al. (2016) presented enhanced absorption, which is one type of “negative” flare originally defined in the visible continuum (Flesch & Oliver 1974; Henoux et al. 1990; Hawley et al. 1995; Ding et al. 2003). Previous studies have shown that enhanced absorption during flares was observed in another helium line, D3 at 5876 Å (Zirin 1980; Liu et al. 2013). It is worth noting that the shapes or sizes of negative flare ribbons are different. In the D3 negative flares, the flare sources are well-defined ribbon-like structures and the absorption was enhanced on the entire ribbons (Liu et al. 2013). In the He I 10830 Å line, the darkening can be found in a large diffused area (Harvey & Recely 1984) or confined on the leading edge of the ribbon (Xu et al. 2016). Such differences may be caused by varying temperature and density in the flaring area or the bandwidth of the prefiler.

There are two formation mechanisms of He I 10830 Å line, photoionization- recombination mechanism (PRM) and collisional-recombination mechanism (CRM). The transition that forms the He I 10830 Å line is in the triplet state of HeI (ortho helium), where the two electrons spin in the same direction of a helium atom. At the typical temperature and density of the chromosphere, the transition from the ground state (parahelium), where the two electrons spin oppositely, to the ortho helium via direct collisional excitation is rare. Instead, in the quiet Sun, EUV or soft X-ray radiation can populate ortho helium via PRM. Helium is ionized by coronal radiation, with recombination and cascades to ortho helium, generating an absorption feature (Goldberg 1939; Andretta & Jones 1997; Centeno et al. 2008). During a flare, nonthermal collisions between flare-accelerated electrons and helium can introduce an alternative pathway to populating ortho helium. Helium can be ionized by these nonthermal collisions, with subsequent
recombinations to ortho helium, which is the CRM mechanism. Determining which mechanism is responsible for the enhanced absorption and emission in flares is important in diagnosing flare-energy transport mechanisms.

Recent numerical studies have shed light on the He I 10830 Å response to flares. Ding et al. (2005) used semi-empirical modeling to conclude that nonthermal CRM plays an important role in producing absorption at the initial phase of flares, though did not have a fully self-consistent model that included both PRM and nonthermal CRM. Using the F-CHROMA database (https://star.pst.qub.ac.uk/wiki/public/solarmodels/start.html), Huang et al. (2020) show that the formation temperature and density of enhanced absorption are about $2 \times 10^4$ K and $6 \times 10^{11}$ cm$^{-3}$, respectively. Once the temperature or density increases above the threshold, the He I 10830 Å line turns from absorption to emission. Their results are consistent with the predictions made by Zirin (1980). More recently, Kerr et al. (2021) presented detailed analysis of He I 10830 Å absorption during flares using RADYN (Carlsson & Stein 1992, 1997; Allred et al. 2015) simulations that included both PRM and nonthermal CRM. The authors confirmed that nonthermal CRM plays a key role in producing the darkening at the beginning of the flare. In their simulations, omitting nonthermal collisions meant that the line did not undergo a period of enhanced absorption. In addition, they found that the level of darkening is related to the properties of the flare-accelerated electrons, with a positive correlation between the low-energy cutoff of the precipitating electron beam. The “harder” the beam (that is, the greater the number of deeply penetrating higher energy electrons in the distribution), the stronger the absorption.

In the previous monochromatic narrowband observations, the Lyot filter was set to the blue wing of the He I line at 10830.05 with a bandpass of 0.5 Å (Zeng et al. 2014; Xu et al. 2016). It is representative of the line’s general behavior if the line profile remains symmetric or the intensity varies in the same direction for the entire line. However, one can imagine scenarios in which a part of the line is in emission while the rest remains in absorption (e.g., due to Doppler motions). So, observations at a single, narrow, spectral position may not represent the characteristic of the entire line profile. Such a special case exists in some modeling results, such as the red profile (at $t = 10$ s) in Figure 1 panel (a) in Huang et al. (2020).

To confirm our previous conclusions that He I 10830 Å undergoes enhanced absorption at the flare ribbon’s narrow leading edge and that those observations were not a serendipitous observation of an unusual line profile, we aimed to observe the 10830 Å line at high spatial resolution and with rough spectral resolution. Such observations will also facilitate a more detailed model-data comparison. In this study, we present a C3.0 flare observed at five different spectral positions around the He I 10830 Å line using the 1.6 m GST (Goode & Cao 2012) at BBSO. The flare was also observed by the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014).

Figure 1. Sample images taken around 17:23 UT for the C3.0 flare that occurred on 2018 May 28. Panel (a): TiO continuum image. Panel (b): He I 10830 red wing +0.8 Å. Panel (c): IRIS SJI 2796 image.

2. Observations

A C3.0 flare that occurred in active region (AR) 12127 on 2018 May 28, peaking around 17:10 UT, was observed by both BBSO/GST and IRIS. BBSO/GST observations were carried out at three different channels, the Broad-Band Filter Imager, Visible Imaging Spectrometer, and Near Infra-Red Imaging Spectropolarimeter (NIRIS; Cao et al. 2012), for TiO, Hα, and He I 10830 Å, respectively. NIRIS was set to the imaging mode without polarization for observations of the He I 10830 Å line at five spectral positions (line center, $\pm 0.4$ and $\pm 0.8$ Å). The spectral calibrations of these two lines are done every day in quiet Sun areas at the beginning of the observations. Multiple flats fields are taken for 10830 to compensate for minor temporal changes of the flat fields. The image scale is about 0′/062 pix$^{-1}$ and the effective cadence for a scan of five spectral positions is 45 s. Figure 1 shows sample images taken in these 3 channels and the IRIS slit-jaw imager (SJI) 2796 Å filter after the flare. The GST images are aligned with SDO/HMI continuum maps and displayed with heliocentric coordinates.

3. Results

This flare shows a circular shape of emission observed in the IRIS SJI UV bands, though GST’s smaller field of view (FOV) only caught a portion of the flare ribbons. There are ribbon-like features under the null point, and we concentrate on the southern ribbon in this study. Other ribbons or foot points are blocked or contaminated by the dark loops of the possible dome structure and highly dynamic fibrils. Because of the short duration, seeing variation, and complex structures, only a few locations with good images, between 17:09 and 17:11 UT in He I 10830, are suitable for analysis. Time-sequence studies, as in Xu et al. (2016), are not possible with this data set. Below
we present a multiwavelength analysis at a specific time, near the flare peak around 17:10 UT, for emission (positive contrast) and enhanced absorption (negative contrast) separately.

### 3.1. Emission

A representative set of images in each of the five spectral positions taken from 17:10:50 UT to 17:11:04 UT, at ±0.8, ±0.4 Å and the line center of the He I 10830 Å line, are shown in Figure 2 panels (a) to (e). The core region covering the target ribbon is outlined by a black box in panel (e) and the small FOV within the box is presented in panel (f). In front of the bright ribbon, there is a faint dark edge, which will be discussed in the next section concerning He I 10830 Å absorption. Two different areas of emission are selected, one immediately behind the ribbon front and one in the trailing edge. They are marked by the black box named “T” and “P” in panel (f), for the trailing component and peak area, respectively. Image contrasts are defined as contrast = (I − b)/b, in which I is the intensity and b is the background intensity. The flaring area is surrounded by several small sunspots, groups of pores, and dark dynamic fibrils. Background selection should not be based solely on the corners of the FOV because the intensities in the corners are much lower than the center due to dominant dark features and relatively weak correction of the AO system. Therefore, we combine two areas, one in the center within a granulation area (b1 in panel (c) of Figure 2) and one from the upper right corner outside the small pore (b2 in panel (c) of Figure 2). They are illustrated on the image at flare time; the actual measurement of the background intensities is carried out on the preflare frames around 17:00:57 UT. The black dots, connected by a dashed curve, in Figure 3 panel (a), show the normalized (to the maximum intensity at −0.8 Å, referring to the right Y-axis) intensity of the background, b. The intensities have been magnified by a factor of 10 to show the difference among the five spectral positions. In principle, the pseudo line profile of the background b is a very shallow absorption curve.

The contrasts of emission at five different wavelengths are listed in Table 1 and plotted in panel (a) of Figure 3 in blue (for the trailing area) and red (for the peak area) colors, and connected by a quadratic function, which is used for illustration purposes only. The standard deviation of contrasts of all pixels in box “T” and “P” is calculated and shown as 1σ uncertainties (arrows). The results show that the contrast enhancement ranges from about 30% to nearly 100% compared to the quiet Sun areas. These values compare well with the modeling results, which reached peak contrasts in excess of 150%–200%, depending on flare strength (e.g., Huang et al. 2020; Kerr et al. 2021). The quadratic curves link the different spectral positions and work as pseudo line profiles, which can be compared qualitatively with modeled spectra. The peak area is close to the propagating ribbon front so that it represents the early stage.
of the emission, following flare-energy deposition (which in the standard flare model is primarily via bombardment of nonthermal electrons). The trailing area is away from the ribbon front and represents a well-developed stage of the flare, where thermal processes are presumed to dominate. Although the seeing conditions are not good enough for a detailed analysis of the temporal behavior, we are able to compare our observations of different spatial features that represent different stages during the flare, with the temporal behavior of the He I 10830 Å line in flare simulations. In their Figure 1, panel (a), Huang et al. (2020) presented two types of He I 10830 Å profiles, a center-reversed (at $t = 2.9$ and $4.3$ s) and a red wing enhanced (at $t = 10$ s). In addition, Kerr et al. (2021) also produced red wing enhanced spectra (see their Figures 6 and 7).

**Figure 3.** Panel (a) shows pseudo line profiles of the He I 10830 Å line in different spatial positions on the flare ribbon, with different colors. Orange: emission profile in the peak flaring area (“P” in panel (f) of Figure 2). Blue: emission profile in the trailing area (“T” in panel (f) of Figure 2). Cyan: absorption profile on the ribbon front. The point of the line center is measured at a different location and therefore highlighted with a red ring. The 1σ uncertainty is calculated from the standard deviation and affected by the area selection. For example, larger areas tend to have larger uncertainties. All colored curves share the same Y-axis on the left side with a unit of percentage of contrast. The black dashed curve links the intensities of the background, using the right Y-axis. The intensities are normalized to the maximum measured at $-0.8$ Å and the absolute amplitudes are magnified by a factor of 10 to illustrate the differences among the five spectral positions. Panel (b) shows the averaged contrasts along the 10 slits (dotted–dashed rectangular box marked as “S” in panel (f) of Figure 2), at $-0.8$ Å.

**Table 1** Contrasts [%] at Five Different Spectral Positions

| Spectral Position     | $-0.8$ Å | $-0.4$ Å | Center | $+0.4$ Å | $+0.8$ Å |
|-----------------------|----------|----------|--------|----------|----------|
| Peak Area (“P”)       | 87 ± 13  | 71 ± 10  | 53 ± 8 | 80 ± 10  | 97 ± 5   |
| Trailing Area (“T”)   | 34 ± 8   | 56 ± 8   | 78 ± 10| 73 ± 11  | 47 ± 13  |
| Front Edge            | $-19$ ± 6| $-17$ ± 8| $-14$ ± 4| $-13$ ± 4| $-10$ ± 4|

**Notes.** Positive values in areas “P” and “T” indicate flare emissions and negative values on the front edge represent enhanced absorptions.

* The slit positions for the line center measurements are quite different from those for the wings. Consequently, the negative contrast at line center is not comparable with the offbands.
Our pseudo profiles show similar behavior. Due to the lack of spectral resolution in 10830 observations, the two types of observed spectra are named “convex” and “concave,” representing higher emission in line core or line wing, respectively. The “convex” spectrum is shown in the trailing area and the “concave” spectrum dominates the peak area.

3.2. Enhanced Absorption

Xu et al. (2016) presented a dark ribbon front in the He I 10830 blue wing (10830.05 ± 0.25 Å). In the multi-spectral-position observation under investigation, similar edges in front of the ribbon with negative contrasts are seen in all five wavelengths channels. The area of 10 slits is highlighted by a dotted–dash line “S” in Figure 2 panel (f). The contrasts along each slit are obtained against the same background area mentioned in the previous section. The average contrasts of the 10 slits are plotted in Figure 3 panel (b). The range of these 10 values at each point along the X-axis is used to evaluate the uncertainty. For instance, at the 9th point, the contrast level varies from −13% to −25%. Therefore, the average contrast is as low as −20% with uncertainties of ±6.0%. The same measurements are carried out for other spectral positions and the results are plotted in Figure 3 panel (a) in cyan color and listed in Table 1. To avoid contamination from other dark features, such as fibrils, slit positions are slightly shifted by 2 or 3 pixels for offbands and significantly differ for the line center. Since the negative contrasts are not measured at a strictly identical location (as we do for the emission), pseudo line profiles of the negative contrasts are less meaningful compared with the emission profiles. The key information here is that the negative contrasts appeared in front of the bright flare ribbon at a level similar to the results in Xu et al. (2016), and in all five wavelength channels. This result suggests that the enhanced absorption on the ribbon front is not caused by the minor absorption embedded in emission profiles, but that the full line profile is undergoing enhanced absorption.

3.3. IRIS UV Spectra

IRIS also observed AR 12712 on 2018 May 28 with a very large 320 step raster. Figure 4 shows a UV 2796 Å IRIS SJI image and a Mg II spectrum. This data set was taken around 17:14 UT, which is the earliest time at which the spectrograph slit has a clear view of the flare ribbon (previously, the slit’s view of the ribbon was obscured by the dome structure). By comparing the locations of the flare ribbons on the IRIS SJI and He I 10830 images, we could identify the ribbon location in the SJI and Mg II spectral images, as pointed out by the red arrow in panels (a) and (b) of Figure 4. The ribbon propagates from north to south, so that the ribbon front is located in the southern edge. Note that here we aim to compare behavior of Mg II h and k lines at the ribbon front, which has propagated slightly south of where we identified the He I 10830 Å ribbon edge at the earlier time to those profiles in the trailing portion of the ribbon. The Mg II spectrum at Y = 239 pixel indicated by the blue bar in panel (b), which is a representative position of the ribbon front, is plotted using blue color in panel (c). We also note that the He I 10830 Å negative contrasts were present at the ribbon front. The Mg II lines at the ribbon front are characterized by a significant central reversal and line broadening. A sample spectrum in the trailing area is selected eight pixels north to the ribbon front (Y = 247 pixel, indicated by the orange bar in panel (b)) and plotted using orange color. The ribbon-trailing spectrum is located within the well-developed flaring area with much larger intensities than the spectrum at the ribbon front. However, in such spectrum the line broadening is reduced and the center reversal is barely seen. The spectral properties and differences at the ribbon front and trailing area found in this study agrees with previous observations (Xu et al. 2016; Panos et al. 2018). Modeling of the Mg II spectra alongside the He I spectra is currently underway to see if we can reproduce these patterns (G. S. Kerr et al. 2022, in preparation).

4. Discussion

In this study, we present the analysis of a C3.0 flare observed on 2018 May 28, at five spectral positions around the He I 10830 Å line. The emission level of 30% ~ 100% contrast and the two types of line profiles (“convex” and “concave”) agree well with previous modeling results (Huang et al. 2020; Kerr et al. 2021). Other kinds of spectra at different stages in the flare evolution likely exist and should be studied with future observations under better seeing conditions and/or better spectral resolutions. Enhanced absorption is detected in front of the moving flare ribbon, which is at a level similar to that reported in Xu et al. (2016). The blue wing tends to have...
stronger enhanced absorption than the red wing, which offers a good feature for comparison to flare models of this line. There is a time gap of $\sim 200$ s between the MgII spectra shown in Figure 4 and the HeI 10830 Å images shown in Figure 2, which are associated with two close but distinct emission peaks in the GOES soft X-ray emission. By inspecting the IRIS SJI images at the times corresponding to the two different peaks, we find that the morphology of the flare emission evolves significantly only in the region located in the left part of the flaring area. The propagation direction and shape of the target flare ribbon near the center of the flaring area did not change substantially. Future observations, ideally with improved temporal and spectral resolutions, should be sought for this purpose. Our results do confirm that single passband observations are suitable for studying the enhanced absorption feature; if a choice must be made, the blue wing offers a cleaner view of the negative contrast.

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ORCID iDs

Xu Yang @ https://orcid.org/0000-0002-3238-0779
Graham S. Kerr @ https://orcid.org/0000-0001-5316-914X

References

Allred, J. C., Kowalski, A. F., & Carlsson, M. 2015, ApJ, 809, 104
Andretta, V., & Jones, H. P. 1997, ApJ, 489, 375
Cao, W., Goode, P. R., Ahn, K., et al. 2012, in ASP Conf. Ser. 463, Second ATST-EAST Meeting: Magnetic Fields from the Photosphere to the Corona, ed. T. R. Rimmele et al. (San Francisco, CA: ASP), 291
Carlsson, M., & Stein, R. F. 1992, ApJL, 397, L59
Carlsson, M., & Stein, R. F. 1997, ApJ, 481, 500
Centeno, R., Trijillo Bueno, J., Uitenbroek, H., & Collados, M. 2008, ApJ, 677, 742
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, SoPh, 289, 2733
Ding, M. D., Li, H., & Fang, C. 2005, A&A, 432, 699
Ding, M. D., Liu, Y., Yeh, C., & Li, J. P. 2003, A&A, 403, 1151
Flesch, T. R., & Oliver, J. P. 1974, ApJL, 189, L127
Goldberg, L. 1939, ApJ, 89, 673
Goode, P. R., & Cao, W. 2012, in ASP Conf. Ser. 463, Second ATST-EAST Meeting: Magnetic Fields from the Photosphere to the Corona, ed. T. R. Rimmele et al. (San Francisco, CA: ASP), 357
Harvey, K. L., & Recely, F. 1984, SoPh, 91, 127
Hawley, S. L., Fisher, G. H., Simon, T., et al. 1995, ApJ, 453, 464
Henoux, J., Aboudarham, J., Brown, J. C., van den Oord, G. H. J., & van Driel-Gesztelyi, L. 1990, A&A, 233, 577
Huang, N., Sadykov, V. M., Xu, Y., Jing, J., & Wang, H. 2020, ApJL, 897, L6
Kerr, G. S., Xu, Y., Allred, J. C., et al. 2021, ApJ, 912, 153
Kobanov, N., Chelpanov, A., & Pulyaev, V. 2018, JASTP, 173, 50
Li, H., You, J., & Du, Q. 2006, SoPh, 235, 107
Li, H., You, J., Yu, X., & Du, Q. 2007, SoPh, 241, 301
Liu, C., Xu, Y., Deng, N., et al. 2013, ApJ, 774, 60
Panos, B., Klein, L., Huwyler, C., et al. 2018, ApJ, 861, 62
Penn, M. J., & Kuhn, J. R. 1995, ApJL, 441, L51
Xu, Y., Cao, W., Ding, M., et al. 2016, ApJ, 819, 89
You, J. Q., & Oertel, G. K. 1992, ApJL, 389, L33
Zeng, Z., Qiu, J., Cao, W., & Judge, P. G. 2014, ApJ, 793, 87
Zirin, H. 1980, ApJ, 235, 618

Vanessa Polito @ https://orcid.org/0000-0002-4980-7126
Viacheslav M. Sadykov @ https://orcid.org/0000-0002-4001-1295
Ju Jing @ https://orcid.org/0000-0002-8179-3625
Haimin Wang @ https://orcid.org/0000-0002-5233-565X