Chromospheric Response during the Precursor and the Main Phase of a B6.4 Flare on 2005 August 20

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Abstract

Solar flare precursors depict a constrained rate of energy release, in contrast to the imminent rapid energy release, which calls for a different regime of plasma processes to be at play. Due to the subtle emission during the precursor phase, its diagnostics remain elusive, revealing either nonthermal electrons (NTEs) or thermal conduction to be the driver. In this regard, we investigate the chromospheric response during various phases of a B6.4 flare on 2005 August 20. Spatiotemporal investigation of flare ribbon enhancement during the precursor phase, carried out using spectra images recorded in several wavelength positions on the H\textalpha line profile, revealed its delayed response (180 s) compared to the X-ray emission, as well as a sequential increment in the width of the line profile, which are indicative of a slow heating process. However, the energy contained in the H\textalpha emission during the precursor phase can reach as high as 80\% of that estimated during the main phase. Additionally, the plasma hydrodynamics during the precursor phase, resulting from the application of a single-loop one-dimensional model, revealed the presence of a power-law extension in the model-generated X-ray spectra, with a flux lower than the RHESSI background. Therefore, our multiwavelength diagnostics and hydrodynamical modeling of the precursor emission indicates the role of a two-stage process. First, reconnection-triggered NTEs, although too small in flux to overcome the observational constraints, thermalize in the upper chromosphere. This leads to the generation of a slow conduction front, which causes plasma heating during the precursor phase.

Key words: conduction – radiation mechanisms: non-thermal – radiation mechanisms: thermal – Sun: flares – Sun: magnetic fields

Supporting material: animation

1. Introduction

Solar flares are violent phenomena occurring in the solar atmosphere that release \(\sim 10^{32}\) erg energy in typically \(10^3\) s. In principle, such phenomena occur in active regions having a complex magnetic field configuration (Jain et al. 2011; Choudhary et al. 2013). Moreover, emission from a strong flare can be recorded from gamma rays to radio wavebands, i.e., covering almost the entire electromagnetic spectrum (Fletcher et al. 2011). Thorough analysis of such a complex and violent phenomenon needs extended theoretical and numerical modeling based on state-of-the-art resolution observations and codes. Despite enormous progress in solar flare investigations, the most applicable 2D model of the energy release in solar flares to date is still the CSHKP model proposed by Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp & Pneuman (1976). Modifications inspired by observational studies, along with theoretical simulations over the years, have resulted in a standard (unified) model of flares (Dennis & Schwartz 1989; Shibata 1999).

According to the standard model of solar flares, magnetic reconnection is understood to be the mechanism working as the engine for converting magnetic energy into kinetic energy of the charged particles (mostly electrons). Electrons accelerated in this manner reach the chromosphere guided by the magnetic field of the flaring region and dump their energy in the dense chromosphere, while a tiny part (roughly \(10^{-5}E_{\text{tot}}\)) of the energy is radiated in the X-ray wavelength in the framework of the thick-target bremsstrahlung (Brown 1972). Most of the energy of the charged particle is also utilized in heating the chromosphere, the transition region, and the coronal plasma attached to the reconnected field lines, as well as sometimes even the photosphere. Subsequently, a sudden increase in the energy of a small volume/kernel of chromosphere results in chromospheric evaporation/ablation. The ambient charged particles thus start filling the loop guided by the flare loop magnetic field and undergo thin-target bremsstrahlung resulting in low-energy (soft) X-ray (SXR) emission. Integrating the temporal evolution of energy release as explained above, SXR emission should always be accompanied by a high-energy (hard) X-ray (HXR) counterpart. In contrast, precursor SXR enhancement has been recorded well before the onset of impulsive HXR emission, as often as in 90\% of the flares studied by Veronig et al. (2002). Therefore, temporal evolution of a typical flare comprehending the aforementioned physical process may be divided into three subintervals, namely: the precursor phase, the impulsive phase, and the gradual (decay) phase. The precursor phase of the flare is most commonly referred to as gradual small-scale enhancements, prominently seen in the SXR and EUV wavebands, prior to the onset of rapid and intensive emission recorded in the HXR and radio wavebands, termed the impulsive phase. However, the post-impulsive phase activity is collectively termed the gradual phase of the flare. While multiwavelength diagnostics of precursor activities reveal a vast variety of processes including (1) discrete and localized X-ray brightenings with the possibility of being detected as early as 50 minutes before the impulsive phase of the flare and filament acceleration (Ohya &...
Shibata 1997; Chifor et al. 2007), (2) slow rise in the filament (Martin 1980; Chifor et al. 2006; Joshi et al. 2011), as well as partial filament eruption (Awasthi et al. 2014), (3) reconnection within various branches of a multi-flux rope system during the precursor phase of a confined flare (Awasthi et al. 2018), and (4) oscillation of a magnetic flux rope (MFR) during the precursor phase suggestive of magnetic restructuring during this phase (Zhou et al. 2016). The underlying mechanism that gives rise to these small intensity-scale activities, as well as its role in the impulsive phase of the flare, is still under debate.

Several studies have been carried out in order to understand the origin of the precursor phase emission. Battaglia et al. (2009) suggested the thermal conduction-driven chromospheric emission to be a possible mechanism of the precursor SXR enhancement. Awasthi et al. (2014), in their study of a solar flare event well-observed in a multiwavelength band, presented an observational signature of the conduction front responsible for the precursor phase emission. However, Falewicz et al. (2011) and Falewicz (2014) found the energy contained in the reconnection-driven nonthermal electrons (NTEs) to be sufficient to produce SXR emission during the precursor phase. They argued that insufficient instrumental sensitivity was responsible for the absence of HXR emission during the precursor phase. Altyntsev et al. (2012) analyzed microwave emission during the precursor, as well as the impulsive phase, and suggested that although nonthermal emission remained present during the precursor phase, it was not sufficient to explain the observed SXR enhancement. However, regardless of the higher sensitivity of the radio instruments in comparison to the existing X-ray detectors, Benz et al. (2017) reported a radio-quiet preflare phase with three well-developed SXR extrusions as recorded by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Battaglia et al. (2014) attempted to search for a chromospheric response due to the conduction front during the precursor phase of a flare using high spatial and temporal cadence observations for one well-observed flare. Their study resulted in the absence of noticeable signatures of the energy transported through conduction at the chromospheric heights. Therefore, it is evident that the study of energy release processes during the precursor phase is yet to reach a consensus.

An in-depth investigation of the chromospheric response is crucial in order to shed light on the physical process taking place at different layers of the solar atmosphere leading to the precursor excursions and their association with the imminent impulsive energy release during the main phase of the flare. Complex dynamical activities of the plasma giving rise to the flare emission, particularly in the chromosphere, can be probed through deriving the characteristics of the Hα line profile (Zarro et al. 1988; Graeter & Kucera 1992; Heinzel et al. 1994; Druett et al. 2017) in the form of a shift in the line center, and the line width. Canfield et al. (1984) investigated the effect of an NTE beam and coronal pressure enhancement on the synthesized Hα line profiles and suggested that increased coronal pressure can cause line profile broadening and an increase in the total intensity of the Hα line. However, only a large flux of high-energy NTEs may result in the Hα profiles having non-Gaussian broad wings. Moreover, their study could associate the line central reversal effects with the heating rate by the NTEs. In contrast, the thermal conduction mechanism may result in a reduced Hα line width and total intensity of the profiles. Huang et al. (2014) investigated the trigger for an observed sequence of pre-eruptive events leading to a filament eruption, as well as coronal mass ejection. Their study revealed that draining plasma into the loop footpoint was associated with the precursor phase and the subsequent filament eruption. Moreover, while several investigations have shown blue asymmetry during the early rise phase of the flare (see Heinzel et al. 1994 and the references therein), the underlying physical processes giving rise to the same remains elusive. In particular, although Heinzel et al. (1994) proposed that electron beam heating with the return current caused the early-stage blueshift in the Hα line profile, a similar effect in the line profile has been reported in the investigation of Graeter & Kucera (1992), who found the erupting filament to be the cause. Further, Kuridze et al. (2015) emphasized the role of the steep gradient in the velocity of emitting plasma in shifting the wavelength of maximum opacity, thus adding another dimension of complexity in the implications obtained merely by the shift in the Hα line profile. Therefore, although the quantification of the Hα line profile provides comprehensive information of the dynamical activities during various stages of the flare evolution, a careful investigation employing co-temporal spectra images, such as those recorded with the Multi-channel Subtractive Double Pass (MSDP) imaging spectrograph (Rompolt 1990; Mein 1991), is inevitable as performed in the present paper.

In this paper, we present a multiwavelength diagnostic of the chromospheric response during various phases of a small B6.4 flare on 2005 August 20. In Section 2, a brief discussion on the observations applied in the present study and the respective instrument is presented. Section 3 deals with the multi-wavelength data analysis, while Section 4 presents an in-depth analysis of the spectra images produced by an MSDP-type spectrograph covering the Hα line center and wings. Section 5 provides a comparative overview of the thermal and non-thermal energy content estimated from the X-ray and Hα observations during various phases of the flare. In Section 6, we present the results of a single-loop, one-dimensional hydrodynamic model, in the context of the observations during various phases of the flare. Section 7 offers the conclusions and insights gained from the present study.

2. Observations and Instrumentation

We study the spatial, temporal, and spectral evolution of a chromospheric response during the precursor and main phases of an SOL2005-08-20T08:09 event, a B6.4 intensity class flare, which occurred in AR 10798 (S10W33) on 2005 August 20. In this regard, we analyze multiwavelength observations provided by the following instruments.

2.1. MSDP

Spectra images of the investigated flare (i.e., two-dimensional images convolved with the Hα line spectra; see Mein 1977 for details) have been collected with the Large Coronagraph (Gnevyshev et al. 1967; Rompolt & Rudawy 1985) equipped with an MSDP imaging spectrograph (Rompolt 1990; Mein 1991) at the Bialkow Observatory of the University of Wroclaw, Poland. The Large Coronagraph (LC) is a classical Lyot-type instrument with a 51 cm diameter main objective and nearly 14.5 m effective focal length, which can also be used as a chromosphere graph (without the artificial Moon). The rectangular entrance window of the MSDP spectrograph is located at the coude-focus of the LC which covers an equivalent area of 325 × 41 arcsec² on the sky plane delimiting the effective field of view (FOV) of the whole system. Because of the limited FOV, scans of various lengths of 15–18 spectra images are usually obtained to cover the
whole flare region, as well as the surrounding area. In this way, effectively an area of $\sim 300 \times 360$ arcsec$^2$ in the plane of sky is covered. The spectrograph has a nine-channel prism-box (Rompolt 1990; Mein 1991) creating $d\lambda = 0.4$ Å steps in wavelength between nine consecutive “channels” at the spectra images. All nine channels at the individual quasi-monochromatic spectra image (waveband = 0.06 Å) show exactly the same area on the Sun, but each of these is recorded in a slightly shifted wavelength band in relation to others in the vicinity of the Hα line (the width of the wavelength band of a single channel is $\Delta \lambda = 0.32$ nm). The spectra images have been recorded with a 12 bit Photometrics KAF1400 CCD camera using 0.57 arcsec per CCD pixel sampling and 40 ms exposure time. The time interval between two consecutive exposures has been nearly 2.8 s, the effective time step between consecutive scans varied between 55 and 68 s, depending upon the change in the observation parameters. The DCF77 time signal receiver was used to record the precise time of each exposure. For each scan we constructed a set of thirteen narrow band nearly monochromatic images of the whole region (up to ±1.2 Å from the Hα line center), as well as the Hα line profile at each pixel in the FOV. The spatial resolution of the obtained images is limited by seeing, on average to about 1 arcsec. We have used Meudon spectroheliograph full-disc observations obtained at 06:20:16 UT as a reference to derive actual solar $X$–$Y$ coordinates of high-resolution MSDP observations. Additionally, Solar and Heliospheric Observatory (SOHO)/MDI full-disc photospheric continuum observation, recorded at 06:24:00 UT, is used for cross-checking the alignment. In the present investigation, we analyze MSDP observations recorded during 06:36 UT–09:00 UT, covering various phases of the flare. However, bad weather conditions during 07:10 UT–07:25 UT led to a gap in the observations for this duration.

2.2. RHESSI

X-ray emission recorded by RHESSI (Lin et al. 2002) during the flare is analyzed to deduce the spatial, temporal, and spectral evolution of the X-ray source. RHESSI records X-ray emission in a 3 keV–20 MeV energy band, employing nine Germanium detectors with a temporal cadence of 4 s, and an energy resolution ranging between 1 to 5 keV. In the case of the analyzed flare, RHESSI recorded the X-ray counts in the “A11” attenuator state over the entire flare. Due to RHESSI night, a data gap occurred between 06:45 and 07:29 UT. We employ data recorded with detectors 2F, 3F, 4F, 5F, 6F, 8F, and 9F for the synthesis of spectra and images. Figure 1 shows the temporal evolution of the X-ray emission of the flare in various energy bands covering 6–25 keV.

2.3. SOHO/EIT

Extreme ultraviolet observations in the 195 Å band, recorded during the flare by an Extreme Ultraviolet Imager Telescope (EIT; Delaboudinière et al. 1995) on board the SOHO have been analyzed. Temporal cadence of such observations is 12 minutes, while the spatial resolution is $\sim 2.6$ arcsec. The temperature coverage of the observed emission from this instrument is in the range of 0.08–2 MK. The temporal evolution of the background-subtracted EUV emission during the flare is plotted in Figure 1.

3. Multiwavelength Diagnostics of the Flaring Plasma during the Precursor and the Main Phase

Multiwavelength emission recorded by various space- and ground-based instruments has been investigated. In the following, we present the temporal, spatial, and spectral diagnostics of the emission corresponding to various phases of the flare.

3.1. Spectral and Spatial Evolution of the X-Ray Emission

We analyze the spatial, temporal, and spectral evolution of the X-ray sources as seen by RHESSI during the flare. The intensity profiles of X-ray emission in various energy bands covering 6–25 keV are plotted in Figure 1. Although enhancement in the energies >12 keV appeared unambiguously only after \(0.08:04\) UT in RHESSI observations, successive and rapid enhancement in the 0.5–4 Å emission (the higher energy channel of GOES) (Figure 1(b)) has been recorded since 07:45 UT, which marks the onset of the main phase of the flare. However, low-energy X-ray emission in the form of several episodes of small-scale humps is recorded in RHESSI as well as in 1–8 Å wavelength bands as early as \(06:00\) UT. A notable trend in the 1–8 Å intensity profile since 06:00 UT is a slow but steady increase in the X-ray emission level despite several intermittent emission peaks, which led us to consider 06:00–07:45 UT to be the precursor phase of the flare investigated in this paper.

The thermal and nonthermal characteristics of the flare plasma are diagnosed by investigating the X-ray emission recorded by the RHESSI mission. For this, first we prepare X-ray spectra with a nonuniform temporal and energy binning in order to achieve sufficient count statistics during various phases of the flare. During 06:00–06:45 UT, and 07:46–07:56 UT, covering the precursor, and a part of the rise phase durations of the flare, the spectra have been prepared with the signal averaged over a period of 120 s, while the time duration for averaging the records is kept to 32 s for the same corresponding to the main phase during 07:56–08:27 UT. Furthermore, the spectra is prepared with the energy binning of 0.3 keV in the 6–10 keV energy band and the same has been increased to 1 keV for the emission in the energies >10 keV. As the X-ray emission originating from the coronal plasma is an aggregated response of thermal and nonthermal processes, we perform a forward-fit of the background-subtracted RHESSI observations with a theoretical spectrum prepared by combining the isothermal ($v_{th}$) and thick-target bremsstrahlung models ($v_{thick}$) available within the SPEX package of SolarSoft5 (Awasthi et al. 2016). The line and continuum emissions in the isothermal model are generated using the CHIANTI atomic database (Dere et al. 1997; Landi et al. 2013), while the NTEs in the spectral shape of the power-law function (Brown 1971) are implemented in the thick-target model. The observed X-ray spectra serve as an input to the fit-procedure in SPEX, which is performed through the mcurvefit.pro routine, based on the nonlinear least-squares Levenberg–Marquardt fitting algorithm. In this, by varying the inherent parameters of the models in an iterative manner, a model spectrum is derived which best-fits the observations. The goodness of the fit is determined by estimating the reduced $\chi^2$ value with the aim to minimize it to “unity.” The spectral fit enabled us to estimate the flare plasma parameters characterizing thermal emission, namely temperature ($T$) and emission measure (EM), while those representing

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nonthermal emission are electron flux, negative spectral index ($\delta$), and lower energy cutoff. Temporal evolution of the aforementioned parameters during various phases of the flare is shown in Figure 2. Moreover, the uncertainties in the fit parameters have also been estimated within the SPEX package by making use of the curvature matrix of the $\chi^2$ hypersurface in the parameter space, assuming that the parameters are well-defined and have symmetric uncertainties of local Gaussian shape (Ireland et al. 2013; Warmuth & Mann 2016a) as shown in the form of error bars over the respective quantities in Figure 2.

During the precursor phase, plasma temperature varies in the range of 9–14 MK, while during the main phase it ranges between 12 and 24 MK. The EM of the plasma reaches a value of $5 \times 10^{17}$ cm$^{-3}$ during the precursor phase, which is retained throughout the main phase. Due to a poor count rate recorded during the precursor phase, the temperature and EM estimations suffer higher uncertainties than that during the main phase. Next, the NTE beam parameters, namely: total electron flux, power-law index, and low-energy cutoff values, as plotted in Figure 2, vary in the range of $(1-7) \times 10^{35}$, 7–14, and 8–10 keV, respectively. We also plot the temporal evolution of the observed X-ray emission in 6–10, 10–14, and 14–25 keV energy bands in the bottom panel of Figure 2 for reference.

Next, we investigate the evolution of the X-ray source morphology during various phases of the flare using X-ray images in X-ray images in various energy bands, reconstructed with the CLEAN algorithm (Hurford et al. 2002). Figure 3 shows the evolution of the X-ray sources along with the magnetic field topology and the loop morphology. The magnetograms obtained from Michelson Doppler Imager (MDI; Scherrer et al. 1995) instrument on board the SOHO mission have been applied. As the SOHO/MDI magnetograms with a high time cadence of one minute were available only until 08:00:00 UT, evolution of the magnetic field parameters has only been estimated within the SPEX package by making use of the curvature matrix of the $\chi^2$ hypersurface in the parameter space, assuming that the parameters are well-defined and have symmetric uncertainties of local Gaussian shape (Ireland et al. 2013; Warmuth & Mann 2016a) as shown in the form of error bars over the respective quantities in Figure 2.
Figure 2. Evolution of plasma parameters, namely: temperature, emission measure, electron flux, power-law index ($\delta_{\text{electron}}$), and cutoff energy (panels (a)–(e)). Panel (f) shows the temporal evolution of the observed X-ray emissions in 6–10, 10–14, and 14–25 keV energy bands. Photon flux in 6–10 keV is reduced by one order for better visibility of the intensity evolution in the high-energy bands.
been comprehensively studied during the precursor phase of the flare. This investigation revealed a persistently increasing trend in both the positive, as well as negative, flux values until 06:18 UT, associated well in time with the onset of the X-ray precursor enhancement recorded in the GOES observations. Subsequently, the flux cancellation is evident, although much clearer in the positive flux evolution, and is plotted in Figure 12 (Appendix A). It might suggest that magnetic reconnection is responsible for triggering the energy release during the precursor phase, in agreement to that revealed in the investigation of Wang et al. (2017) of two precursor excursions of a M6.5 flare on 2015 June 22. EUV images obtained in 195 Å during the flare have been analyzed in order to distinguish the morphological changes in the loop connectivity from the precursor to the main phase of the flare. Temporal evolution of background-subtracted emission in 195 Å is plotted in Figure 1, which reveals enhanced EUV emission during the precursor phase. The coronal loops’ connectivity in conjunction with the photospheric magnetic field topology is investigated through the iso-intensity contours of the magnetic field value 800 Gauss of both the positive and negative polarities plotted over the 195 Å EUV images as shown in Figure 3. Co-spatial emission during the precursor and main phase is seen from the time sequence of the EUV images. We further over-plot the contours of 80% of the maximum intensity of X-ray images in 6–10, 10–15, and 15–35 keV. From this multi-wavelength emission representation, the flare activity in the corona appears to be predominantly concentrated over the western (positive) polarity of the active region. Furthermore, a systematic shift in the centroid location of the X-ray emission toward the positive polarity is found from the precursor to the main phase.

4. Chromospheric Response during Various Phases of the Flare

The quasi-monochromatic images reconstructed using MSDP data in the Hα ±1.2 Å wavelength band have been analyzed to study the chromospheric response during various phases of the flare. Figure 4 shows the time sequence of images obtained in Hα line center as well as in ±0.6 Å in the line wings at the instances 06:36:41 UT (precursor), 08:09:17 UT (flare maximum), and 08:20:23 UT (gradual phase). The iso-contours of 80% of the maximum intensity of the co-temporal X-ray images in 6–10, 10–15, and 15–35 keV energy bands are also drawn on the images. In addition, for reference purposes, we have also drawn the iso-intensity contour of the magnetic field strength 800 Gauss as shown in the top panel of Figure 4.

Figure 4 shows that during the precursor phase (panel (a)), the emitting regions in the Hα line center and in the soft X-ray emission (6–10 keV) are spatially linked. Predominant emissions in the Hα waveband, as well as in the SXR energy band, are found to originate close to the positive polarity. Furthermore, at the maximum point of the main phase, i.e., at 08:09:17 UT (panel (b)), we note enhanced Hα brightenings in the form of well-defined kernels. A systematic shift of the source centroid in the Hα, as well as in X-ray wavelengths, toward positive polarity while transition of the flare from the precursor (panel (a)) phase to the gradual (panel (c)) phase is found. Comparative morphological analysis of the Hα emission during the precursor phase revealed diffused spatial distribution of the sources, while those appearing in the form of distinct kernels were found during the impulsive phase of the flare. Furthermore, the dynamics of the excursions tend to sequentially shift westwards toward the positive polarity similar to that exhibited by the X-ray contours. Irrespective of several minor activities in the filament evolution associated with the flaring region, any sequential filament activity associated with various phases of the flare remained ambiguous. Nevertheless, this implication is limited by the moderate spatial resolution of the MSDP observations. A quantitative investigation of the time evolution of the Hα line profile in various phases of the flare follows.

4.1. Spatiotemporal Diagnostics of the Hα Line Profile in Various Phases of the Flare

In order to quantify the emission in the Hα line center as well as in the wings, we investigate the spectral evolution of the flare ribbon in several individual subregions denoting the areas covering significant activity during various phases of the flare. As shown in panel (a) of Figure 5, we have chosen 15 regions of interest (ROIs) of circular shape. The line profile of the quiet Sun \(I_\text{quiet}(\lambda, t)\) corresponding to each instance of the observation is derived by averaging the intensity within the two rectangular regions (panel (a); white box), away from the flaring region, from the sequence of images recorded at the respective time \(t\) in different wavelength positions across the Hα line. Next, we derive the intensities corresponding to
various wavelength positions of the Hα line profile by averaging a matrix of dimension 3 × 3 pixels centered at the position of maximum intensity within the ROI. In this way, we have derived a time evolution of the Hα line profile corresponding to all the ROIs for the entire duration of the flare. Hα intensities have been standardized to physical units (erg s⁻¹ sr⁻¹ cm⁻² Hz⁻¹) using the quiet-Sun reference spectrum of David (1961; see Appendix B). The investigation of the intensity evolution for all the 15 subregions corresponding to various locations over the flare ribbon can be categorized in two distinctive trends, where the first exhibits predominant activity during the precursor phase, while the latter shows enhancement during both the precursor as well as the main phases of the flare as discussed in Appendix C. For further detailed investigation, we concentrate on the activities within ROIs 9, 11, and 13, which comprehend the evolution trends derived from all of the 15 ROIs. The time profile of the intensity in the Hα line center for the aforementioned ROIs is plotted in panels (b)–(d) of Figure 5, respectively.

The time profile of the Hα line center intensity corresponding to ROI 9 has an evolution similar to the SXR light curve during the precursor phase of the flare (Figure 5(b)). However, intensity evolution in the Hα line center corresponding to ROI 11 (Figure 5(c)) is found to be well-correlated with the precursor as well as the main phase of the flare. The intensity profile corresponding to the ROI 13 (Figure 5(d)) exhibits rapid growth during the maximum of the impulsive phase of the flare, while that during the precursor and the rise
phase of the flare is relatively less in comparison to that estimated from ROI 9 and 11. Therefore, as discussed above, we consider the ROIs 9, 11, and 13, as representative cases for different phases of the flare for further investigation.

The time sequence of the H\(\alpha\) line profile evolution corresponding to ROIs 9, 11, and 13, presented in Figure 6, enables us to make a comparative investigation of the chromospheric response during various phases of the flare. In view of quantifying the profiles in terms of line broadening, we first calculate the net emission by subtracting the observed profile with the co-temporal quiet-Sun profile (Falewicz et al. 2011). The resultant net emission profile is then fitted with the Gaussian function employing the “gaussfit” procedure available in IDL. The net emission (shown as dotted symbols), as well as a best-fit Gaussian function (full line) for several time instances, are plotted in panels (d)–(f) of Figure 6. The full-width-half-maximum (FWHM) of the best fit to the H\(\alpha\) emission profile is considered as the line width. From the observations corresponding to ROI 9, we find the widths of the line profiles to be sequentially increasing from 0.87 to 1.08 Å from the precursor phase to the rise phase of the flare. However, such a trend in the line width broadening is not evident in the profiles obtained from ROIs 11 and 13. One of the possible interpretations of the line profile broadening phenomena is the enhanced pressure in the flare loop (Canfield et al. 1984), hence further investigation of the MSDP spectra images is crucial in this context as performed in the following.

During the maximum point of the impulsive phase of the flare, the H\(\alpha\) line profile corresponding to the ROIs 11 and 13 show redshifted emission profiles. Since the location of ROI 11 and 13 is co-spatial to the HXR emission centroid (see Figure 4(b)) during the maximum point of the impulsive phase, we argue such profile to be caused by the intense heating of the chromosphere by the NTEs (Canfield et al. 1990). In contrast, the line profiles for ROI 9 have never turned in a complete emission profile during the whole period of investigation.

We estimate the relative excess emission in the H\(\alpha\) line center as well as in the wings using the following equation:

\[
I_{\text{excess}}(\lambda, t, \text{ROI}) = \frac{I_{\text{obs}}(\lambda, t, \text{ROI}) - I_{qs}(\lambda, t)}{I_{qs}(\lambda, t)}
\]

where \(I_{\text{obs}}(\lambda, t, \text{ROI})\) is the intensity recorded in a particular wavelength \(\lambda\) at time “\(t\)" within the ROI, whereas \(I_{qs}(\lambda, t)\) is the intensity of the quiet Sun corresponding to the wavelength at the same instance as that of \(I_{\text{obs}}\). The temporal evolution of the excess in intensity for the H\(\alpha\) line center as well as \(\pm 0.6\) Å for ROIs 9 and 11 is shown in Figure 7. The excess intensity.

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**Figure 5.** Spatiotemporal analysis of the flare ribbon through the spectra images obtained by the MSDP. Fifteen circular-shaped subregions of interest (ROIs) over the entire flare ribbon considered for the investigation of the H\(\alpha\) line profile are drawn in yellow in panel (a). Regions have been sequentially numbered from the left to the right side, while only ROIs 9 (green), 11 (red), and 13 (blue) have been annotated, as they are considered for further detailed analysis. The two rectangles, covering the quiet Sun, at the top and bottom of the flaring region, denote the area over which the quiet-Sun profile is estimated. Panels (b)–(d) show the temporal evolution of emission recorded in the H\(\alpha\) line center for ROIs 9, 11, and 13, respectively. The time profiles of the X-ray photon flux in 6–12 and 12–25 keV are also plotted. The dotted gray line represents the onset of the main phase of the flare.
profile for ROI 13 exhibits an evolution similar to that of ROI 11.

A comparison of the excess emission profile \( I_{\text{excess}} \) corresponding to ROI 9 (Figure 7) is made with the SXR emission in 6–12 keV. The SXR intensity peak at 07:31 UT can be correlated with the first prominent maxima \( (P1) \) among several excursions during the precursor phase in the time profile of the \( \text{H} \alpha \) line center as well as the wings. We note a relative time delay in the peak time of the \( \text{H} \alpha \) emission with respect to that in the SXR intensity profile to be approximately 180 s. The uncertainty in the relative time delay, due to the moderate temporal cadence of the images made available from the MSDP spectrograph, can be as large as \( \sim 60 \) s. In contrast, the second peak \( (P2) \) in the \( \text{H} \alpha \) time profile, corresponding to the impulsive phase of the flare, appeared without measurable delay compared with the respective SXR peak. The relatively quick response of the \( \text{H} \alpha \) emission to the SXR emission during the impulsive phase compared to that during the precursor phase implies chromospheric heating through NTE in this phase (Radziszewski et al. 2011). However, another slow heating mechanism during the precursor phase may be responsible for the delayed response of the \( \text{H} \alpha \) emission originating from the chromospheric height. Similarly, the investigation of intensity excess in ROI 11, shown in the right panel of Figure 7, resulted in a well-correlated temporal evolution.

**Figure 6.** (a)–(c): Time sequence of the \( \text{H} \alpha \) line profiles corresponding to ROIs 9, 11, and 13. The \( \text{H} \alpha \) line profile of the quiet Sun is also shown in gray, while a vertical dotted line indicates the position of the line center. The net emission profile for ROIs 9, 11, and 13 is plotted in panels (d)–(f), respectively, with colored dot symbols, while the resultant Gauss-fit (full line) is also over-plotted with the same color. Different colors represent different time instances of observations and are annotated in panel (d), while the full-width-half-maximum of the respective best-fit Gaussian function is also noted for all the ROIs considered in the investigation.
of emission in the Hα line center as well as in the wings with the SXR profile. We have not been able to derive any noticeable delay between the maxima of the Hα emission profile with that of the SXR time profile during the main phase of the flare.

Additionally, the plots shown in Figure 7 revealed asymmetric responses of the red and blue wings of the profile during various phases of the flare at different locations on the flare ribbon. Until 07:10 UT during the precursor phase, ROI 9 exhibited a comparatively stronger emission in the blue wing than in the red wing, while the same is not distinctly depicted by ROI 11. In contrast, since the onset of the peak P1, both ROIs exhibit red asymmetry. Red asymmetry in the Hα line profiles is derived from ROI 11 since the onset of the main phase of the flare may be caused by the NTEs, considering the fact that we did not find a measurable delay between the emission peaks in the intensity profiles of the Hα line center and the soft X-ray emission during this phase. However, due to a delayed response of the Hα emission (≈180 s) compared with the SXR emission, the red asymmetry during peak P1 may be due to the down-flows being comparatively slower than the NTEs of the impulsive phase, possibly a thermal conduction front. Furthermore, while the blue asymmetry during the onset of the flare has been reported in the past (Heinzel et al. 1994 and references therein), our observations present the signature of blue asymmetry as early as one hour before the onset of the main phase. One of the most plausible interpretations of such a prolonged blue asymmetry in the early stage of the flare may be due to the presence of a moving absorption feature, such as a filament neighboring the ROIs. It is of note that temporal evolution of the emission in the blue and red wing corresponding to ROI 9 reveals a more distinctive nature than that derived from ROI 11, revealing a nonuniform chromospheric response corresponding to different locations of the flare ribbon. Therefore, we further investigate the morphology and dynamics of the emission and absorption features. In this regard, we first prepare a time sequence of composite blue wing images by summing the co-temporal MSDP images recorded in Hα−0.2, Hα−0.4, and Hα−0.6 Å wavelengths. Similarly, the red wing composite images have been prepared by adding the co-temporal MSDP spectra images recorded in Hα+0.2, Hα +0.4, and Hα+0.6 Å wavelength positions of the Hα line. A sequence of the blue and red wing composite images at 06:36:41 UT (first MSDP record), 07:33:45 UT (corresponding to P1), and at 07:51:35 UT (corresponding to peak P2) is shown in Figure 8.

From Figure 8, we learn that separate portions of a complex filament structure are visible in the blue and red wing composite images. In particular, in the vicinity of ROI 9, part of a dark filament material (denoted by a red arrow) appears only in the red wing images since the start of the MSDP observations at 06:36 UT. In contrast, the same structure is not evident in the associated blue wing images. Therefore, prolonged blue asymmetry during the precursor phase as seen in the Hα line profiles corresponding to ROI 9 may be attributed to a moving absorption feature, possibly referring to the draining of the filamentary material similar to that investigated in Huang et al. (2014). Moreover, Graeter & Kucera (1992), in their investigation of an Hα line profile during a limb flare, found blue-shifted emission profiles during the onset phase of the flare to be originating from the erupting filament. Furthermore, the morphological evolution of the ribbon emission, as shown in Figure 8, and the movie, reveals a multi-loop morphology of the active region as well as propagating brightness along the Hα ribbon toward the western (positive) polarity (in agreement with the behavior of the X-ray sources synthesized from RHESSI observations (Figure 4)). Although the on-disk location of the flaring region concedes the altitude information of the flare loops, we propose that ROI 9 represents the footpoint of a low-lying loop, heated during the precursor phase. Next, propagation of the ribbon brightening implies that reconnection takes place sequentially in the overlying loops (Ohayama & Shibata 1997; Awasthi et al. 2014). The footpoint of one such loop, brightened during the main phase of the flare, is represented by ROI 11. This may contribute to the nonuniform nature of line asymmetry depicted by ROIs 9 and 11.

5. Energetics of the Flare

We estimate the energy content in the thermal and nonthermal processes, as well as that released from the chromosphere during various phases of the flare. The energy radiated from the flare in
the Hα line is estimated from the calibrated line profiles (see Section 4.1), derived from MSDP observations, during various phases of the flare. For this purpose, we integrate the intensity of the line profile within the wavelength range Hα–0.6 Å to Hα+0.6 Å. We intentionally exclude the far wing observations (±0.6 to ±1.2 Å) of the Hα line owing to the relatively moderate quality of observations in the said wavelength range. Next, the thermal energetics of the flare is estimated employing the following equation (Saint-Hilaire & Benz 2005).

\[ E_{\text{thermal}} = 3k_b T \sqrt{EM \cdot V \cdot f}. \]  

Here \( k_b \) refers to Boltzmann’s constant, \( T \) is the temperature of the flaring plasma, while \( V \) represents the volume of the flaring region, and the same has been approximated to be \( A^{3/2} \) where \( A \) is the area representing 20% of the maximum intensity in the 195 Å images. “\( f \)” corresponds to the filling factor and is considered to be equal to unity in this case. We employ the temperature and EM of the plasma, derived by the spectral fit of RHESSI observations to estimate the thermal energetics corresponding to the flare observation. In the left panel of Figure 9, the time evolution of the thermal energy content, as well as the energy emitted in the Hα waveband, is plotted. We have also derived the nonthermal energy content during various phases of the flare with the IDL routine “calc_nontherm_electron_energy_flux.pro” available in the SPEX package of Solarsoft, in which NTE beam parameters estimated from the spectral fit of the RHESSI spectra have been supplied as input. Temporal evolution of the nonthermal energy content is shown in the right panel of Figure 9. In Table 1, the maximum values of the energy content derived within various wavebands during the precursor and main phase of the flare are listed.

The energy radiated in the form of the Hα line profile during the precursor phase amounts to 80% of that estimated during the main phase of the flare (Table 1). Moreover, nonthermal energy content is found to be relatively higher than the Hα emission by approximately two orders of magnitude during the precursor phase, while by four orders at the maximum point of the main phase of the flare. In agreement to this, Canfield et al. (1991) obtained the ratio of the Hα flux to the nonthermal flux and found it to vary in the range of \( 10^{-3} - 10^{-1} \) for flares of various intensity classes. Furthermore, comparative analysis revealed that the rate of the thermal energy release is approximately 1–2 orders less than the nonthermal energy release rate, in agreement with that obtained by Awasthi et al. (2014), Warmuth & Mann (2016b), and Aschwanden et al. (2017).

6. One-dimensional Hydrodynamic Simulation of the Thermal and Nonthermal Emission

We synthesize the X-ray spectrum during various phases of the flare by applying a one-dimensional hydrodynamic
Our model makes use of the spectral parameters derived from forward-fitting of the observed X-ray spectra to simulate the evolution of the plasma using a modified Naval Research Laboratory (NRL) Solar Flux Tube Model (Mariska et al. 1982; Mariska & Poland 1985; Falewicz et al. 2009). The spectral properties that serve as an input to the aforementioned model include the nonthermal electron beam (NTE) parameters, such as total electron flux, spectral index, and cutoff energy. Furthermore, the loop geometry as determined from RHESSI observations during the main phase of the flare (while from the EIT images during the precursor phase) is provided as an input to the model. This and other input parameters are listed in Table 2.

The implementation of a modified hydrodynamic one-dimensional NRL Solar Flux Tube Model is initiated with the assumption that the flare plasma is confined in a rigid and semi-circular loop. The constant strength of the magnetic field is considered to be 200 G, following the estimations made by Aschwanden (2005). Moreover, a constant cross section of the loop, provided as an input to the code, is estimated in conformity from the soft X-ray images made available by a GOES/SXI instrument as well as the images in 195 Å wavelength from the SOHO/EIT observations. The half-length of the flaring loop, derived from the aforementioned observations, is $3.047 \times 10^8$ cm. In the next step of the model, the plasma inside the loop is set to be heated by the energy flux delivered to the loop solely by NTEs (Falewicz et al. 2011; Falewicz 2014). Subsequently, in order to achieve the best conformity between the synthetic (calculated) and observed GOES intensity flux in the 1–8 Å range (Falewicz 2014), the low-energy cutoff energies ($E_c$) of the electron spectra, provided as an input to the model, is set to vary for each time step. The steady-state solution of the spatial and spectral distributions of the NTEs are derived for each time step of the model using the Fokker–Planck theory (McTieman & Petrosian 1990).

The spatial distributions of the plasma thermodynamic parameters, as derived from our model, have been applied to derive the X-ray thermal and nonthermal emissions as well as the integral fluxes in the energy ranges of interest. The thermal EM of the optically thin plasma was based on the X-ray continuum and line emission calculated using the CHIANTI (version 7.1) atomic code (Dere et al. 1997; Landi et al. 2006). For the plasma temperatures above $10^7$ K, the elemental abundances are based on a coronal abundance set ( Feldman & Laming 2000), while below $10^5$ K, photospheric abundances were applied. Ionization equilibrium by Mazzotta et al. (1998) and solar corona abundances for both the lines and continuum have been applied ( Feldman et al. 1992). In Figure 10, we show the spatial distribution of the emission in 6–12 keV and 12–25 keV energy bands derived from our model at two instances corresponding to the precursor and the main phase, respectively. A comparative investigation of the thermal and nonthermal spectra corresponding to observations as well as that resulting from the HD model is drawn in Figure 11. The X-ray spectrum corresponding to RHESSI observations is estimated employing the fit parameters obtained from the application of the SPEX package. Employing the aforementioned procedure on the parameters derived from the HD numerical model, we calculate the model X-ray spectra. From the X-ray spectrum during the precursor phase, shown in panel (a) of Figure 11, we find the nonthermal component of the spectra that resulted from the model to be well below the background level. A similar trend is seen in panel (b) of the figure, which corresponds to the X-ray line radiation (X $10^3$ erg s$^{-1}$ cm$^{-2}$) for the Hα line (black) and X-ray observations (red). The thermal (left panel) and nonthermal (right panel) energy content estimated using the spectral-fitting of RHESSI observations are plotted and scaled according to the right y-axis. The gray line demarcates the onset of the main phase with the precursor phase of the flare.

**Table 1**

| Energy Content | Precursor Phase | Main Phase |
|----------------|----------------|------------|
| Hα             | $2.05 \times 10^8$ | $2.3 \times 10^8$ |
| Thermal        | $4 \times 10^8$    | $4.3 \times 10^8$ |
| Nonthermal     | $2.3 \times 10^9$  | $1.1 \times 10^{11}$ |

**Table 2**

| Loop Parameter | Precursor Phase | Main Phase |
|----------------|----------------|------------|
| Half-length (cm) | $3.05 \times 10^3$ | $3.05 \times 10^5$ |
| Flux-tube radius (cm) | $1.2 \times 10^5$ | $1.5 \times 10^5$ |
| Initial pressure at base (dyn cm$^{-2}$) | 6 | 8 |
Figure 10. Spatial distribution of the emission along the flare loop in 6–12 keV and 12–25 keV energy bands during the precursor and main phases of the flare in the left and right panels, respectively.

to the second episode of the precursor emission. A completely developed SXR and HXR emission, significantly above the RHESSI background, has been derived during the main phase of the flare, as plotted in Figure 11(c). The time evolution of the emitted flux in the energy bands 6–12 keV and 12–25 keV, resulting from the model, is plotted in panel (d) of the figure. The comparison of the time evolution of the model flux, drawn in red, with that observed during the precursor phase shows that the flux in the 12–25 keV energy band remains below the observed count level. In order to compute the dependence of the model output on the input geometric parameters of the flare loop, we ran the HD code for additional cases in which the input geometrical parameters, namely loop length \(l\) and radius \(r\), have been increased (and decreased) from their original value by 20% constituting four sets \(((l-0.21, r-0.2r), (l-0.21, r+0.2r), (l+0.21, r-0.2r), (l+0.21, r+0.2r))\). The thermal and nonthermal characteristics of the plasma resulting from the aforementioned four cases of the model run are further used to synthesize the model X-ray spectrum. The maximum and minimum deviation of the photon flux of the aforementioned set of X-ray spectra at each energy with respect to the original model X-ray spectra, which is derived employing an unaltered set of geometrical parameters (green), is considered as the upper and lower limit of uncertainties, respectively, as shown in the form of error bars (green) in Figure 11. It may be noted that the uncertainties are not significantly large. Therefore, with the model results, we argue that during the precursor phase, the high-energy photons’ flux is insufficient to overcome the RHESSI detector sensitivity threshold.

7. Conclusion and Discussion

We carried out an investigation of the chromospheric response and flare energetics during the precursor and main phase of an SOL 2005-08-20T08:09 event. Spatiotemporal investigation of flare ribbons as seen in the spectra images, recorded by MSDP in 12 wavelength positions on the \(H_\alpha\) line profile, revealed a delayed response (180 s) of the \(H_\alpha\) emission compared to the X-ray intensity profile evolution during the precursor phase. In contrast, no observable delay in \(H_\alpha\) and X-ray emission peaks could be measured during the main phase of the flare, which is suggestive of NTEs being the driver of chromospheric heating (Radziszewski et al. 2011) during the impulsive phase. Also, the precursor emission appears to be a consequence of the relatively slow heating process. Furthermore, a quantitative investigation of the \(H_\alpha\) line profiles, estimated from several subregions of interest (ROIs) on the flare ribbon, revealed a sequential increment in the line width of the profile during the precursor phase, which may be associated with the pressure enhancement in the flare loop (Canfield et al. 1984). In agreement to this, we found increased EM resulting from the spectral fit of the observed X-ray emission during the precursor phase.

The investigation of line asymmetry in the \(H_\alpha\) emission profiles during the precursor phase revealed comparatively stronger emission in the blue wing than in the red wing of the \(H_\alpha\) line corresponding to a few locations on the flare ribbon. While the blue asymmetry during the rise phase of the flare has been reported in the past (Heinzel et al. 1994, Kuridze et al. 2015 and references therein), our observations reveal prolonged blue wing enhancement as early as an hour before the commencement of the impulsive phase of the flare. In this regard, we investigated the morphological and dynamical evolution of the precursor activities in the blue and red wing images of the \(H_\alpha\) line, which revealed the presence of a moving absorption feature (filament material), predominately appearing only in the composite red wing \(H_\alpha\) images, in the vicinity and possibly crossing the locations which depict blue asymmetry. Thus, the most plausible explanation for the prolonged “apparent” blue wing enhancement during the precursor phase is asymmetric absorption (additional to the red wing) offered by the draining filament material (Huang et al. 2014) to the \(H_\alpha\) line wings. Furthermore, the \(H_\alpha\) line profiles exhibit red asymmetry during the entire flare except during the aforementioned period of blue asymmetry. During the maximum point of the impulsive phase of the flare, the same may be attributed to the NTEs, owing to the fact that there is no definitive delay between the respective intensity profile peaks. However, a delayed response of the \(H_\alpha\) emission compared with the SXR emission during the precursor phase implies that the redshift in the \(H_\alpha\) emission during this phase is caused by the down-flows being comparatively slower than the NTEs of the impulsive phase, possibly due to a thermal conduction front. Energy content in the \(H_\alpha\) line during the precursor phase reaches a significant fraction (80%) of that estimated during the main phase. In this regard, we investigate the flare plasma hydrodynamics during the precursor phase from the application of a single-loop one-dimensional model, which revealed the presence of a high-energy power-law tail (>10 keV) in the model-generated X-ray spectrum, however, with the flux values lower than the RHESSI background. Therefore, our multwavelength diagnostics, along with the hydrodynamical modeling of the precursor emission, suggest that NTEs’ flux, although very small, carries sufficient energy to fulfill the requirements of an energy budget for plasma heating during this phase. In conclusion, we propose
the chromospheric response during the precursor phase to be the consequence of a two-stage process. In this, reconnection-generated NTEs thermalize high in the upper chromosphere during this phase as it contains low energy (Reep et al. 2016). Subsequently, the energy deposited by NTEs is transported down to the lower chromosphere via conduction. This scenario requires further detailed investigation employing time-correlation analysis of multiwavelength emission representing various altitudes of the solar atmosphere.

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Appendix A
Temporal Evolution of the Active Region Magnetic Flux

In view of quantifying the signature of the magnetic flux emergence or cancellation during various phases of the flare, we analyze one minute cadence magnetograms made available by the MDI instrument aboard the SOHO mission during the
time interval 05:00–10:00 UT. The signed magnetic flux corresponding to both polarities has been derived by employing the technique adopted by Savcheva et al. (2014). In this, we first fit the histogram of the magnetic field values within the active region with a Gaussian function. The noise level in the respective magnetogram, assigned by the full-width-half-maximum of the best-fit Gaussian function, is estimated to vary in the range of 50–90 Gauss for the sequence of magnetograms analyzed in the present investigation. The pixels having magnetic field above the noise level have been included in deriving the flux. Moreover, the area foreshortening due to the projection effect, and the deviation of the LOS magnetic field ($B_{\text{los}}$) with the radial field ($B_r$) have been taken care of by the multiplication of $(\sec \theta)^2$, where $\theta$ is the angular distance from the disk center. The resulting positive and negative flux is plotted in Figure 12. From the evolution,
although the high time (one minute) cadence evolution contains a large amount of noise, a five minute smoothed evolution (shown in red) reveals a slow but steady increase in the positive and negative flux values until 06:18 UT, closely associated in time with the onset of the GOES X-ray precursor enhancements (blue dotted line). Following this, the flux cancellation is evident, although much clearer in the positive flux evolution.

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**Appendix B**

**Calibration of the Hα Line Profile Using DAVID**

The line profiles shown in Figure 5 are calibrated with the use of the DAVID (David 1961) reference spectrum of the Hα line profile for the quiet Sun. In this regard, first we prepare a time sequence of quiet-Sun Hα profiles (x, y, λ, t) from the MSDP spectra images by averaging over the counts within two rectangles indicative of the quiet Sun (Figure 5; white box). Next, the ratio \( R(\lambda, t) \) of the observed quiet-Sun Hα profile and the DAVID (quiet Sun) reference profile is calculated, which serves as a calibration scale for standardizing the observed line profiles in physical units (\( \text{erg s}^{-1} \text{sr}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \)).

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**Appendix C**

**Temporal Evolution of Individual ROIs**

Temporal evolution of emission in the Hα line center wavelength corresponding to all the ROIs (except ROIs 9, 11, and 13), drawn in Figure 5(a) are plotted in Figure 13. This

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**Figure 13.** Temporal evolution of the emission in the Hα line center wavelength corresponding to the ROIs along the flare ribbon, other than those plotted in Figure 5.
reveals that while the main phase of the flare is pronounced in almost all of the ROIs simultaneously, only a few exhibit prominent emission during the precursor phase. Therefore, we made a further in-depth investigation of the temporal and spectral evolution of the emission associated with only ROI 9, 11, and 13, as they comprehend the intensity evolution trend of all the ROIs.

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