SOLAR FLARE CHROMOSPHERIC LINE EMISSION: COMPARISON BETWEEN IBIS HIGH-RESOLUTION OBSERVATIONS AND RADIATIVE HYDRODYNAMIC SIMULATIONS

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ABSTRACT

Solar flares involve impulsive energy release, which results in enhanced radiation over a broad spectral range and a wide range of heights. In particular, line emission from the chromosphere can provide critical diagnostics of plasma heating processes. Thus, a direct comparison between high-resolution spectroscopic observations and advanced numerical modeling results could be extremely valuable, but has not yet been attempted. In this paper, we present such a self-consistent investigation of an M3.0 flare observed by the Dunn Solar Telescope’s Interferometric Bi-dimensional Spectrometer (IBIS) on 2011 September 24 which we have modeled using the radiative hydrodynamic code RADYN. We obtained images and spectra of the flaring region with IBIS in H\textalpha\ 6563 Å and Ca II 8542 Å, and with RHESSI in X-rays. The latter observations were used to infer the non-thermal electron population, which was passed to RADYN to simulate the atmospheric response to electron collisional heating. We then synthesized spectral lines and compared their shapes and intensities to those observed by IBIS and found a general agreement. In particular, the synthetic Ca II 8542 Å profile fits well to the observed profile, while the synthetic H\textalpha\ profile is fainter in the core than for the observation. This indicates that H\textalpha\ emission is more responsive to the non-thermal electron flux than the Ca II 8542 Å emission. We suggest that it is necessary to refine the energy input and other processes to resolve this discrepancy.

Key words: hydrodynamics – line: profiles – radiative transfer – Sun: chromosphere – Sun: flares

1. INTRODUCTION

Energy release (e.g., by magnetic reconnection) in solar flares generally results in particle acceleration, plasma heating, and plasma wave (or turbulence) generation. Most of the released energy is transported by the accelerated particles downward along magnetic field lines and deposited in the dense chromosphere by Coulomb collisions with ambient plasma in the so-called thick target model (e.g., Brown 1971; Petrosian 1973; Lin & Hudson 1976). Some energy may be transported by thermal conduction from directly heated coronal plasma (e.g., Zarro & Lemen 1988; Battaglia et al. 2009), and possibly by plasma waves (e.g., Fletcher & Hudson 2008; Haerendel 2009). Observational signatures of the energy deposition include radiation in X-rays via bremsstrahlung of the electrons, gamma-rays via the interaction of accelerated ions with background ions, various lines (e.g., H\textalpha\), and continuum emission from the heated plasma. These observations can provide useful diagnostics and help us to constrain the mechanisms of energy release and particle acceleration, a fundamental question for solar flares.

Strong chromospheric lines such as H\textalpha\ and Ca II 8542 Å are formed under the conditions of non-local thermal equilibrium (non-LTE) and represent the response of the lower atmosphere to flare heating. Understanding line formation is crucial for a correct interpretation of the observations and evolution of the line intensities and profiles. Spectroscopic observations of such emission are primarily obtained from ground-based facilities, which have several advantages over space telescopes. Among these advantages are the flexibility of real-time adjustments of pointing and exposure times, and wide ranges of available observing modes and filters. However, because of the limited field of view (FOV; as a trade-off for high spatial resolution), our limited capability to predict flares and seeing, and our limited weather conditions, such ground-based spectroscopic observations of flares are rare (e.g., Fischer et al. 2012; Kleint 2012; Deng et al. 2013) and thus very valuable.

Numerical modeling of flare line emission is a necessary step to interpret observational data, and subsequently to constrain flare mechanisms. Early modeling of atmospheric line emission was based on empirical flaring atmosphere models (e.g., Canfield et al. 1984; Fang et al. 1993) or on radiative transfer simulations of an electron-beam-heated chromosphere (e.g., Fisher et al. 1985; Gan & Fang 1990; Ding et al. 1998), Ding & Fang (2001) and Berlicki (2007) later studied how the precipitation of electrons from the corona affects the line profiles. Kašparová et al. (2009) focused on subsecond-scale variations and solved the one-dimensional (1D) radiative hydrodynamics of a solar atmosphere subjected to subsecond electron beam heating to study the H\textalpha\ line emission. More sophisticated later models involved non-LTE radiative hydrodynamic calculations on timescales up to several tens of seconds; Allred et al. (2005) injected a power-law electron beam at the apex of a loop and tracked the atmospheric response and how the H\textalpha\ line evolved over time in response to the flux of electrons.

In this paper, we present a self-consistent, detailed comparison of line profiles from high-resolution spectroscopic flare observations and advanced radiative transfer hydrodynamic simulations using observationally inferred electron spectra as inputs. Such a comprehensive investigation has not been attempted in the past and can offer new insights to flare dynamics. Specifically, we obtain H\textalpha\ and Ca II 8542 Å line profiles of an M-class flare from the Interferometric Bi-
Figure 1. Temporal evolution of the flux measured on 2011 September 24. (a) GOES SXR flux measured every 3 s showing the M3.0 flare and the preceding and succeeding M2.8 and M5.8 flares from the same AR. (b) RHESSI count rates in colored solid lines and GOES 1–8 Å flux and its time derivative in black dotted lines, arbitrarily shifted vertically. The two vertical dashed lines indicate the impulsive phase.

2. OBSERVATIONS

On 2011 September 24, an M3.0 class flare occurred in the NOAA active region (AR) 11302. As shown in Figure 1, this flare started at 19:09 UT, reaching its maximum at 19:21 in the GOES 1–8 Å flux and ending at 19:41 UT. RHESSI detected HXRs from the beginning of the impulsive phase (19:08) until 19:24 UT. DST/IBIS observed footpoint emission from the chromosphere in Hα and Ca ii 8542 Å from 19:18 to 19:35 UT. The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO) observed the flare in (extreme) ultraviolet; the 1700 Å images of the flare ribbons were used to estimate the cross-sectional area of the flare loop.

2.1. Chromospheric Line Observations by IBIS

IBIS is a dual Fabry–Perot system, capable of full-Stokes dual beam polarimetry of different spectral lines. The spectral lines and six polarization states are scanned sequentially and reconstructed into images of the Stokes vector during the data reduction process. During our observations, we scanned the chromospheric Hα 6563 Å and Ca ii 8542 Å lines and the photospheric Fe i 6302 Å line. Each line scan (with all polarization states and wavelength points) took about 25 s, giving an overall cadence of about 95 s (including overhead such as filter wheel motions).

The IBIS data reduction was performed using our graphical user interface and included corrections for the dark and gain, the alignment of all channels, the wavelength shift due to the collimated Fabry–Perot mount, and the prefilter transmission profile. Speckle-reconstructed images from a simultaneous broadband (white light) camera were used to destretch all spectral channels to remove variations due to seeing. A polarimetric calibration was also performed but is not relevant for our study because we only analyze the intensity profiles. The flare occurred relatively late during the observing day, by which time the atmosphere around the telescope is usually heated up and the seeing is not ideal. Depending on the spectral line, only 3–4 of the 10 scans had stable and favorable seeing to be used for this paper.

The line profiles were averaged along the ribbon. We estimated the area of the footpoints with pixels whose values are above 2500 DN, which is equal to a flux of 31,250 DN s⁻¹. This corresponds to ≈50% of the maximum intensity. The contours of this intensity level are illustrated in Figure 2.

2.1.1. Hα Observations

The Hα line is one of the most commonly observed lines in flares because of its high contrast, and thus it provides useful diagnostics. However, its interpretation is complex because the emission originates from a broad range of heights, from the upper photosphere to the lower chromosphere, and it is sensitive to the photospheric non-thermal electrons precipitating into the chromosphere (Kasparová et al. 2009).

There have been only a few published observations which show the temporal evolution of the Hα profiles from the start of a flare because of the difficulty in setting and holding the spectrograph slit on a flare footpoint (e.g., Kvičala et al. 1961; Canfield & Gunkler 1985; Radziszewski et al. 2007, 2011; Deng et al. 2013). With IBIS we obtained three Hα scans with good seeing, starting after the impulsive phase, at 19:22:40, 19:24:15, and 19:32:09 UT; each scan lasted 27 s and included 24 wavelength points in a wavelength range of ±2 Å from the line center.

2.1.2. Ca ii 8542 Å Observations

The Ca ii infrared triplet (λ = 8498, 8542 and 8662 Å) provides a useful diagnostic of the solar chromosphere because these lines result from the transition between the upper 4p⁡2P_{1/2,3/2} levels and the lower metastable 3d⁡2D_{3/2,5/2} levels. (There are no allowed electric dipole transitions to the ground state.)

The Ca ii 8542 Å line is a natural tracer of solar activity, having a dual nature: its outer wings sample the solar photosphere and the intensity in the far wings is very sensitive...
to the presence of magnetic structures (see Leenaarts et al. 2006), while the core is affected by chromospheric motions. Despite this and the fact that at near-infrared (near-IR) wavelengths the terrestrial atmospheric turbulence is reduced, Ca II infrared triplet observations are still scarce and only possible with ground-based instruments. In this paper, we use imaging spectroscopy in the Ca II 8542 Å line. IBIS scanned the line within 25 s, including 23 wavelength points along a spectral range of ±2.3 Å from the line center. The observation times with good seeing started at 19:22:15, 19:23:49, 19:26:59, and 19:30:08 UT.

Figure 2 shows two snapshots from SDO of AR 11302 at 19:24 UT (top). The box denotes the FOV of IBIS, which was centered on a small pore west of the AR and covered one of the flare ribbons. The bottom row shows example images from IBIS with their wavelengths labeled. While the blue wing images (6561.2 and 8541.1 Å) show a filament in the lower left corner and brightening due to the ribbon emission, the images near the line cores (6562.9 and 8542.0 Å) resemble the emission of AIA 304. During our observations, the ribbon is seen to expand and the filament becomes smaller and weaker in intensity.

2.2. RHESSI Observations

RHESSI had full coverage of the impulsive phase of the flare and part of the decay phase until its sunset, which started at 19:23:52 UT (see Figure 1).

Using the CLEAN algorithm, we reconstructed images at 25–50 keV integrated over 52 s intervals from 19:08:52 to 19:35:44. These images revealed two HXR footpoint sources and a loop top source at later times (see Figure 3). The western footpoint is brighter and moves faster than the eastern one, which is located in a stronger magnetic field. Such asymmetric footpoint emission is understood to be a result of asymmetric magnetic mirroring (e.g., Wang et al. 1995; Jin & Ding 2007; Liu et al. 2009; Yang et al. 2012).

2.2.1. Inferring the Non-thermal Electron Distribution

We can infer the non-thermal electron distribution, and thus its energy flux, by analyzing RHESSI X-ray spectra. The moderate count rates of this M3.0 flare allow imaging spectroscopy of spatially resolved sources only during the HXR peak of the impulsive phase. To cover the temporal
evolution of the flare, we thus chose to fit the spatially integrated spectra which are dominated by the western HXR footpoint (see Figure 3) that coincides with the flare kernel position observed by IBIS. This provides reasonable diagnostics for the electron energy flux as an input to our RADYN simulation of that kernel.

Because each of RHESSI’s nine germanium detectors has slightly different characteristics and makes independent measurements, we analyzed the spectra of individual detectors separately. We then used the means and standard deviations of the fitting parameters to obtain the best-fit parameter and uncertainties. This has several advantages (e.g., avoiding energy smearing) over the conventional approach of directly fitting the average count spectra of all detectors (for details, see, Liu et al. 2008; Milligan & Dennis 2009). We excluded detectors 2 and 7 because of their abnormally high threshold and/or low energy resolution (Smith et al. 2002). We also excluded detector 6 due to its consistently higher $\chi^2$ values of the fitting results than those of the other detectors. For each of the remaining six detectors, we obtained photon spectra by integrating 30 s intervals from 19:09:30 to 19:13:00 UT and 60 s intervals from 19:13:00 to 19:23:52 UT until the spacecraft night.

Using the standard Object Spectral Executive software package (Brown et al. 2006), we applied corrections for albedo, instrumental emission lines, pulse pileup, and the detector response matrix. We fitted the spectra with a thermal component plus a thick-target, non-thermal component consisting of a broken power law,

$$F(E) = (\delta - 1) \frac{T_c}{E_c} \left( \frac{E}{E_c} \right)^{-\delta},$$

for energies $E > E_c$ and a power law with a fixed index $\delta = -2$ for $E < E_c$. Here $T_c = \int_{E_c}^{\infty} F(E) \, dE$ is the total electron flux above $E_c$.

Figure 4(a) shows a spectrum of detector 4, as an example, during the impulsive phase, from which we can clearly see the dominance by the thermal component at low energies and by the non-thermal component at high energies. The green and blue lines show the fitted thermal and non-thermal components, respectively, and the red line is the total fit, summing all of the components.

The temporal evolution of the power-law index $\delta$ and energy cutoff $E_c$ of the non-thermal component are shown in Figures 5(a) and (b). We find a soft–hard–soft spectral evolution with the hardest spectra (lowest $\delta$) occurring at 19:12–19:15 UT.

From RHESSI we obtain the total rate of injection of electrons. To estimate the flux of electrons (or energy flux $\mathcal{E}(E) = E \times F(E)$) within the loop, it requires the knowledge of its cross-sectional area. The spatial resolution ($\geq 7''$) of the combined RHESSI detectors 3–9 used for HXR imaging is insufficient to resolve the flare footpoints. We thus approximated this area with SDO/AIA 1700 Å (1''2 resolution) kernels within the blue contours at 75% of the maximum intensity, as
shown in Figure 6. This approximation is justified by the fact that the primary 1700 Å kernel of the largest area and highest intensity is cospatial with the RHESSI HXR footprint, as shown in Figure 6. Similar cospatiality between Hα kernels and HXR footpoints has also been reported (e.g., Liu et al. 2007). However, we also note some small 1700 Å kernels without a corresponding HXR source, which could be caused in part by RHESSI’s limited dynamic range of the order of 1:10.

As the flare evolves, the contours associated with the AIA 1700 Å easternmost footpoint are no longer cospatially aligned with the RHESSI 25–50 keV emission. The western footprint (observed by IBIS) is the main contributor to the HXR flux and still coincides with the 1700 Å emission. In addition, we also see HXR emission at different locations than 1700 Å emission (see, e.g., Figures 6(c) and (d)). One possibility is that such HXRs are emitted from the loop top source (see Figure 3(f)). Nevertheless, this mismatch could result in an overestimate of the flare loop cross-sectional area, and thus an underestimate of the electron energy flux. We estimated that the uncertainty in the inferred area is about 16%.

Images taken between 19:11 and 19:13 UT contain several saturated pixels which we discarded by imposing an upper threshold of 16000 DN. The resulting areas were then interpolated to the time intervals used for RHESSI spectral fitting and are shown in Figure 5(d). Finally, by dividing the electron power by the estimated loop cross-sectional area, we obtained the electron energy flux, whose temporal evolution is shown in Figure 5(e).

3. RADYN SIMULATIONS

We used the RADYN code of Carlsson & Stein (1997), including the modifications of Abbott & Hawley (1999) and Allred et al. (2005), to simulate the radiative hydrodynamic response of the lower atmosphere to energy deposition by non-thermal electrons in a single flare loop.

3.1. General Description of the RADYN Code

The RADYN code simultaneously solves the equations of hydrodynamics, population conservation, and radiative transfer implicitly for a one-dimensional adaptive grid (Dorfi & Drury 1987), as described by Carlsson & Stein (1992).

For radiative transfer calculations, atoms important to the chromospheric energy balance are treated in non-LTE. These include six-level plus continuum hydrogen, six-level plus continuum, singly ionized calcium, nine-level plus continuum helium, and four-level plus continuum, singly ionized...
magnesium. Line transitions treated in detail are listed in Table 1 of Abbett & Hawley (1999). A complete redistribution is assumed for all of the lines, except for the Lyman transitions in which partial frequency redistribution is mimicked by truncating the profiles at 10 Doppler widths (Milkey & Mihalas 1973). Other atomic species are included in the calculation as background continua in LTE, using the Uppsalla opacity package of Gustafsson (1973).

The addition of hydrodynamic effects due to gravity, thermal conduction, and compressional viscosity to the original RADYN code was described by Abbett & Hawley (1999). Later additions by Allred et al. (2005) included photoionization heating by high-temperature, soft X-ray emitting plasma, optically thin cooling due to thermal bremsstrahlung and collisionally excited metal transitions, and conductive flux limits to avoid unphysical values in the transition region of large temperature gradients.

### 3.2. Simulation Setup

We assumed a single quarter circle loop geometry in a plane-parallel model atmosphere, discretized in 191 grid points. The model loop is 10 Mm in height. We assume a symmetric boundary condition at the loop apex ($z = 10$ Mm). We note from the observations (Figure 6) that the footpoints appear to move during the flare but not more than its diameter so that our assumption of a single loop is a reasonable approximation.

The initial atmosphere (Figure 7) was adopted from the FP2 model of Abbett & Hawley (1999), which is generated by adding a transition region and corona to the model atmosphere of Carlsson & Stein (1997). The temperature was fixed at $10^6$ K at the loop top and no external heating was provided. This allowed the atmosphere to relax to a hydrodynamic equilibrium state.

Initially, the bottom boundary is located in the upper photosphere; the chromosphere is at 0.9 Mm from the bottom of the loop and the transition region is at a distance of 1.56 Mm from the bottom. During the evolution of the atmosphere, we assume open boundaries at the bottom and apex of the loop, extrapolating if necessary.

The non-thermal electron heating was calculated from the power-law spectrum provided by RHESSI spectral fits (see Figure 5). It was included in RADYN as a source of external heating in the equation of internal energy conservation ($Q$ term of Equation (3) in Abbett & Hawley 1999) and has been updated at every integration time interval based on RHESSI data. Intermediate times have been interpolated.

### 3.3. Chromospheric Response to Non-thermal Electrons

In general, the hydrodynamic evolution of the atmosphere is qualitatively similar to the F09 case reported by Abbett & Hawley (1999). Here, we focus on a narrow region within a distance range of $z = 0.62$–2.7 Mm, as shown in Figure 8, which covers the upper chromosphere and transition region. This is the region where the dynamic evolution relevant to the Hα and CaII 8542 Å line emission occurs.

The electrons injected at the loop apex travel downward, losing energy by Coulomb collision, and they heat the chromospheric plasma. This leads to an overpressure which drives chromospheric evaporation with a plasma upflow starting at about 5 s (19:09:33). This also causes the transition region to move upward (see, e.g., the violet dotted line at 19:11:43 in Figure 8).

As time proceeds and the injected non-thermal electron flux decreases, the atmosphere relaxes (see Figure 5). The temperature in the corona and the position of the transition region are directly related to the flux of the injected electrons. This explains the small displacements of the transition region which can be seen over time in Figure 8 in the lines illustrating
the spatial distribution at 19:18:28 (green), 19:20:43 (yellow), and 19:23:52 (red).

3.4. Formation and Evolution of Spectral Lines

In order to compare the synthetic Hα and Ca II 8542 Å profiles with the observations, we integrate the model intensities at each wavelength for 25 and 27 s, respectively, which is the cadence of the observed profiles. A constant microturbulent velocity of 4.5 km s\(^{-1}\) has been applied to compensate for the lack of small-scale random motions in the model (de la Cruz Rodríguez et al. 2012).

Since the atmosphere at the beginning of the run is in a condition of equilibrium, we treat the line profile at this time as a quiet Sun profile, which is subtracted from the intensity profiles at other times, obtaining the so-called excess line profile (Henoux et al. 1998; Matsumoto et al. 2008), which will allow us to better interpret how the flux of electrons affects the flare emission. The observed Hα and Ca II 8542 Å profiles have a wavelength range of 3.8 and 4 Å which is also used to display the simulated profiles.

In order to better understand how atmospheric evolution affects the chromospheric emission, we write the formal solution of the transfer equation for emerging intensity (Carlsson & Stein 1997):

\[
I^0_\nu = \frac{1}{\mu} \int \int S_\nu e^{-\tau_\nu} d\tau d\nu = \frac{1}{\mu} \int \chi_\nu \int S_\nu e^{-\tau_\nu} dz = \frac{1}{\mu} \int \chi_\nu \int C_\nu dz, \tag{2}
\]

where \(\chi_\nu\) is the monochromatic opacity per unit volume; \(S_\nu\) is the source function, which is defined as the ratio between the emissivity and the opacity of the atmosphere; \(\tau_\nu\) is the monochromatic optical depth; and the integrand \(C_\nu\) is the so-called intensity contribution function, which represents the emergent intensity emanating from height \(z\).

3.4.1. Evolution of the Hα Line Profile

The top row of Figure 9 shows the synthesized Hα excess profiles, which are asymmetric during the early stage of the flare and become almost symmetric later when the atmosphere relaxes. The line profile including the quiet Sun emission (red solid line in the right column of Figure 9) shows a dip in the line core.

By integrating the intensity along the line profile, and subtracting the quiet Sun emission, we estimated the evolution of the Hα excess flux over time. Figure 5(f) shows the Hα light curve where flux has been averaged during the integration time of each RHESSI spectrum. As the plasma is pushed upward, chromospheric evaporation takes place and the Hα flux decreases. After 19:14:24, the atmosphere is more stable and the Hα flux varies with the flux of the injected non-thermal electrons.

Between 19:10 and 19:13, the density population at the energy level \(n_1\) of the hydrogen atom decreases by almost a factor of two with respect to the density population at the energy level \(n_2\) (see Figure 10). Therefore, the ratio \(n_2/n_1\) at this time range decreases. The fact that an Hα photon is emitted by the transition from \(n_2\) to \(n_1\) explains the decrease of the Hα flux at these times. Calcium atoms have a similar behavior, which explains the similar decrease shown in Figure 5(g).

The top row of Figure 11 shows the intensity contribution function, \(C_\nu\) (increasing from bright to dark), for Hα at the same times as in Figure 9. The line frequencies are in velocity units, where positive velocities represent plasma moving upward, toward the corona, and negative velocities denote material moving downwards. The blue line represents the atmospheric velocity stratification and the black line shows the line profile (including the quiet Sun emission, as the red profiles of Figure 9). The green line represents the height at which \(\tau_\nu = 1\), showing us that the height formation of Hα wings is coming from the lower chromosphere (\(\approx 0.2\) Mm) and is constant over time, while the height formation of the core varies over time during the two minutes, moving toward lower heights.

Studying how the contribution function changes in time (Figure 11) with height and wavelength, we found that the Hα emission profile becomes broad and centrally reversed not only due to non-thermal effects when the atmosphere is bombarded by energetic electrons (Canfield et al. 1984), but also due to the temperature spatial distribution and the sudden behavior change of the source function in a very thin atmospheric layer.

3.4.2. Evolution of the Ca II 8542 Å Line Profile

The synthesized Ca II 8542 Å excess profiles are shown in the bottom row of Figure 9. The asymmetry in the line profile at early times is not as prominent as for Hα and during the flare the line becomes almost symmetric, especially in the core.

To obtain the temporal evolution of the Ca II 8542 Å intensity, we integrated the intensity along the line profile with the quiet Sun subtracted (Figure 5(g)). The Ca II 8542 Å excess light curve follows a similar behavior as for Hα, with both fluxes peaking at the same time.

Following Equation (2), the intensity contribution function \(C_\nu\) for the Ca II 8542 Å line is represented in the bottom row of Figure 11. We can see that \(C_\nu\) becomes stronger in the core of the line and presents a symmetric behavior in the wings, being
sensitive to plasma velocity changes. The monochromatic optical depth (green line) shows us that the formation of the wings is constant in time and located below 0.2 Mm; the height formation of the core moves toward lower heights for almost seven minutes. Afterwards, it is stable at 1.05 Mm.

4. COMPARING OBSERVED AND SYNTHETIC LINE PROFILES

*RHESSI* entered night at 19:23:52 UT, whereas the first available IBIS observation with decent seeing started at 19:22:24 UT. The two observations thus overlapped for \( \approx 1 \) minute. In the following section, we will compare the synthetic profiles obtained from the radiative hydrodynamic code, using the *RHESSI* spectral information as input, with the line profiles observed by IBIS at 19:22:40 UT for H\( \alpha \) and at 19:22:15 UT for Ca II 8542 Å.

4.1. Calibration of the Quiet Sun Profiles

To compare the observed line profiles with the synthetic profiles, we first have to calibrate the spectral lines of IBIS and RADYN to the same reference system. We use the continuum emission of the Fourier Transform Spectrometer (FTS) atlas taken at the McMath–Pierce Telescope (Brault & Neckel 1999) as reference. By doing so, both the observed and synthetic profiles can be calibrated and normalized to the continuum.

In order to calibrate the lines to the continuum of the FTS atlas, we multiplied the quiet Sun line intensity by a factor such that the distance between the line and the FTS atlas is minimal at the continuum (see Figure 12).

As mentioned in Section 2.1, the H\( \alpha \) and Ca II 8542 Å lines observed by IBIS had a wavelength width of 2 and 2.3 Å with respect to the line center, not reaching the continuum. Therefore, we fit the available spectral range to the FTS atlas. The synthetic profiles were properly adjusted to the FTS continuum.

Our synthesized profiles for the quiet Sun are narrower and steeper than the observations, in agreement with Leenaarts et al. (2009). As several authors (Cauzzi et al. 2008; de la Cruz Rodríguez et al. 2011, 2012) explained previously, there are three principal reasons for this discrepancy.

1. In general, 1D simulation (even if they take into account the dynamics of the atmosphere) cannot catch all of the structuring and small scales that are present in the chromosphere.
2. If the spatial resolution of the simulation is not high enough, the width of the average (spatio-temporal)
profile is lower because the hydrodynamic simulations do not contain the necessary small-scale turbulence and the small-scale motions are missing in the model. As Leenaarts (2010) mentions, the increase in grid resolution causes an increase in amplitude of the velocity variations in the middle and upper chromosphere, and hence also causes a widening of the average profile.

3. Because of the higher opacities, synthetic lines usually show a much darker line core than the FTS atlas. This may be attributed to a low heating rate in simulations.

Figure 12 shows the resulting IBIS and RADYN lines fit to the FTS atlas after the calibration. The vertical error bars associated to the IBIS profile in Figure 12(a) show the difference between the observed and the synthetic emission during the flare at different wavelength positions. The intensity difference between both Hα lines in the wings is due to the poor fit of the IBIS Hα profile to the continuum, because it is a very broad line and the observations covered only a wavelength range of 4 Å.

After the quiet Sun profiles were calibrated and normalized to the continuum, we applied the normalization factor to the flaring line profiles and in Figure 13 compared them with the IBIS Hα and Ca II 8542 Å observations Hα and Ca II 8542 Å at 19:22:40 and 19:22:15 UT, respectively.

For a better comparison of the shape of both line profiles, the synthetic profile has been shifted by 0.05 erg s⁻¹ cm⁻² Å⁻¹ in order to align the wings of both lines. The line has been scaled to fit at the core, as shown by the green line of Figure 13.

4.2. Hα Line Profiles

Figure 13(a) compares the Hα excess line profile obtained from RADYN (red) and observed by IBIS (blue) from 19:22:40 to 19:23:07 UT. As mentioned in Section 4.1, the intensity shift between both profiles at the wings of the line is due to the uncertainty of the continuum fit.

The core of the simulated line is ≈23% less bright than the observation and the wings are slightly narrow, as discussed in Section 4.1. The Hα core is sensitive to the temperature pattern due to the low mass of the hydrogen atom (Leenaarts et al. 2012), which can contribute to the difference in the core emission. The green profile in Figure 13(a) is the synthetic profile scaled to fit at the core and at the continuum of the IBIS profile and the vertical error bar represents the difference between the observed and synthetic emission at different wavelength positions, calculated for this time.

The standard NLTE line formation assumption of statistical equilibrium does not properly fit the observations because of the slow collisional and radiative transition rates when compared to the hydrodynamical timescale. In addition, the Lyα and β lines at least need to be modeled with partial frequency redistribution (PRD) because of their strong influence on the Hα line (Leenaarts 2010). The inclusion of these effects could significantly increase the Hα opacity. Thus, proper modeling of the Hα line requires fully time-dependent radiative transfer with PRD in tandem with the hydrodynamic evolution, a Herculean task that has not been done in 1D hydrodynamic simulations because all 1D simulations have thus far performed radiative transfer assuming complete redistribution (Allred et al. 2005; Kašparová et al. 2009; Varady et al. 2010).

As Leenaarts et al. (2012) explain, PRD effects can be approximated by truncating the Lyman line profiles. RADYN truncates the Lyman line profiles ±64 km s⁻¹ away from the line center frequency. This is a reasonable approximation, with
the effect that we obtain higher formation heights than if we assumed PRD.

4.3. \textit{Ca} \textsc{ii} 8542 Å Line Profiles

Figure 13(b) compares IBIS (blue line) and RADYN (red line) in the time range 19:22:15–19:22:42 UT, showing good agreement between both profiles. The green line profile is the synthetic profile scaled to fit the core and the continuum of the IBIS profile.

As mentioned by Smith & Drake (1987), assuming complete spectral redistribution for the scattered photons may be a poor approximation for \textit{Ca} \textsc{ii} 8542 Å, which could explain the increased intensity in the core. Leenaarts & Carlsson (2009) and Leenaarts et al. (2009) investigated the formation of \textit{Ca} \textsc{ii} 8542 Å in 3D MHD models that extended into the corona, finding that the 3D effects are important, especially in the core of the line. Considering these two statements and that both lines differ in the core for only ≈2.4%, our synthetic \textit{Ca} \textsc{ii} 8542 Å profile fits the observations very well. As discussed in Section 4.1, the wings area is narrower in the simulated profile because of a lack of small-scale dynamics in the model.

From the study of the monochromatically optical depth of the second panel, $\tau = 1$ (green line in Figure 11), we determine that \textit{Ca} \textsc{ii} 8542 Å is formed between 0.15 Mm in the wings and 1.05 Mm in the core, while H$\alpha$ is formed at 0.2 Mm in the wings of the line and 1.15 Mm at the core. Even if both lines had a nearly similar formation height range and the same atmospheric conditions, \textit{Ca} \textsc{ii} 8542 Å better fits the observations than does H$\alpha$. Since the 3 d $^2D_{3/2,5/2}$ levels are metastable, they can only be populated from below by collisional excitation, strengthening the sensitivity of the \textit{Ca} \textsc{ii} infrared triplet to the local temperature. On the other hand, the lower energy level of H$\alpha$ is 10 eV higher than \textit{Ca} \textsc{ii} 8542 Å, where the population is very sensitive to the atmospheric parameters, explaining the different behavior of the two lines.

5. SUMMARY AND DISCUSSION

In this paper, we have presented a self-consistent, data-driven radiative hydrodynamic simulation of an M3.0 flare and its comparison with high-resolution spectroscopic observations by the IBIS instrument. By fitting the X-ray spectra of this flare observed by \textit{RHESSI}, we inferred the flux of the non-thermal accelerated electrons which we then used as an input to the RADYN code. The RADYN code incorporates careful treatments of atomic and molecular physics together with radiative transfer and hydrodynamics, allowing us to study the evolution of the flaring atmosphere as well as the detailed chromospheric emission. We synthesized the H$\alpha$ and \textit{Ca} \textsc{ii} 8542 Å excess line profiles, which generally agree with those observed by IBIS. Specifically, as shown in Figure 13, the synthesized \textit{Ca} \textsc{ii} 8542 Å emission is consistent with observations within the expected uncertainties, while the H$\alpha$ synthetic line is ≈23% fainter in the core than the observations. Both synthetic lines have shapes similar to the observed line, but the synthetic lines exhibit a typical flattening in the core due to an overestimate of the opacity, as discussed in Section 4.1.

There are several limitations in our approach, which could be improved in the future. For example, solar flares are complex and dynamically three-dimensional in nature. The current 1D models are not yet capable of handling this properly and solving the equations of non-equilibrium and non-LTE optically thick radiative transfer in multiple dimensions. The inclusion of a quasi-thermal component in the electron distribution, in addition to the non-thermal component, and a proper treatment of the electron transport process can play an important role in the estimation of the electron heating rate (e.g., Liu et al. 2009). Moreover, taking into account the uncertainties in the \textit{RHESSI} fitting parameters and the measurement of the area may reduce the differences between the synthesized and observed line profiles.

As noted by Leenaarts (2010), the dominant chromospheric energy loss in the quiet Sun occurs through radiation in strong lines, and a comprehensive model of the chromosphere cannot be constructed without the inclusion of the underlying
photosphere and upper convection zone and the overlying lower corona. Our RADYN code lacks a detailed treatment of photospheric radiation, which could potentially contribute to the small discrepancies between the synthetic and observed lines. A better reproduction of the observations may require higher resolution, larger computational domains, an improved treatment of radiation, and non-equilibrium hydrogen ionization. To improve the modeling of the hydrogen transitions, in particular H\(\alpha\), 3D NLTE time-dependent radiative transfer codes including PRD would be a considerable undertaking.

By increasing the flux of the injected electrons by a factor of two, the atmosphere evolves faster at initial times and as a result the line profiles show red-wing asymmetries at early times. During the impulsive phase of the flare, the H\(\alpha\) emission increases by a factor of 1.2 and Ca\(\text{II}\) 8542 Å by factor of 1.5. At later times, the lines are fainter decreasing by a factor of 1.3 at 19:23:52 UT for H\(\alpha\) and a factor of 1.1 for Ca\(\text{II}\) 8542 Å, mostly because the flattening at the line core becomes more obvious. There is still a mismatch at the wings of the lines, which are still narrower than the observations.

Extending the analysis to a mult iwavelength study similar to the one presented by Milligan et al. (2014) demonstrates the value of bringing together observations over a broad spectral range. The combination of ground-based observations, such as those of H\(\alpha\) and Ca\(\text{II}\) 8542 Å, with the recently launched Interface Region Imaging Spectrograph (IRIS; de Pontieu et al. 2014) would provide more detailed information about the response of the chromosphere during a solar flare.

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