The Astrophysical Journal, 846:40 (10pp), 2017 September 1

© 2017. The American Astronomical Society. All rights reserved.

The Formation of IRIS Diagnostics. IX. The Formation of the C I 135.58 NM Line in the Solar Atmosphere

Hsiao-Hsuan Lin1, Mats Carlsson1, and Jorrit Leenaarts1,2

1 Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway; mats.carlsson@astro.uio.no, jorrit.leenaarts@astro.su.se
2 Institute for Solar Physics, Department of Astronomy, Stockholm University, AlbaNova University Centre, SE-106 91 Stockholm, Sweden

Abstract

The C I 135.58 nm line is located in the wavelength range of NASA’s Interface Region Imaging Spectrograph (IRIS) small explorer mission. We study the formation and diagnostic potential of this line by means of non local-thermodynamic-equilibrium modeling, employing both 1D and 3D radiation-magnetohydrodynamic models. The C I/C II ionization balance is strongly influenced by photoionization by Lyα emission. The emission in the C I 135.58 nm line is dominated by a recombination cascade and the line forming region is optically thick. The Doppler shift of the line correlates strongly with the vertical velocity in its line forming region, which is typically located at 1.5 Mm height. With IRIS, the C I 135.58 nm line is usually observed together with the O I 135.56 nm line, and from the Doppler shift of both lines, we obtain the velocity difference between the line forming regions of the two lines. From the ratio of the C I/O I line core intensity, we can determine the distance between the C I and the O I forming layers. Combined with the velocity difference, the velocity gradient at mid-chromospheric heights can be derived. The C I/O I total intensity line ratio is correlated with the inverse of the electron density in the mid-chromosphere. We conclude that the C I 135.58 nm line is an excellent probe of the middle chromosphere by itself, and together with the O I 135.56 nm line the two lines provide even more information, which complements other powerful chromospheric diagnostics of IRIS such as the Mg II h and k lines and the C II lines around 133.5 nm.

Key words: radiative transfer – Sun: atmosphere – Sun: chromosphere – Sun: UV radiation

1. Introduction

The C I 135.58 nm line (2s2 2p2 1D2 – 2s2 2p 4d 3F2) is in the wavelength range of the NASA small explorer mission Interface Region Imaging Spectrograph (IRIS) and is normally observed together with the nearby O I 135.56 nm line (Lin & Carlsson 2015). Their line cores are formed in the mid-chromosphere, unlike other strong lines that IRIS covers, such as Mg II h and k (Leenaarts et al. 2013a, 2013b; Pereira et al. 2013) and the C II 133.5 nm multiplet (Rathore & Carlsson 2015; Rathore et al. 2015a, 2015b), whose cores usually form in the upper chromosphere or transition region.

Already, the SKYLAB mission revealed interesting behavior of the C I/O I line ratio: during a solar flare, the C I 135.58 nm line gets stronger than the O I 135.56 nm line, the opposite of the behavior in the quiet Sun (Cheng et al. 1980). It is thus clear that the C I 135.58 nm line may provide diagnostics of the solar chromosphere, especially when combined with observations in the O I 135.56 nm line.

Lites & Cook (1979) modeled C I–C IV with semi-empirical models of flares. The C I 123.9 nm continuum is blended with the Lyα wing and the hydrogen radiative transfer was therefore solved together with carbon to take into account the effect of Lyα on the C I/C II ionization balance. It is important to include effects of partial redistribution (PRD) in the Lyα line profile. According to their calculations, the C I/C II ionization balance depends on the Lyα wing intensity and the Lyman continuum, but is insensitive to C I line transfer.

Mauas et al. (1989) presented a more complete study of the carbon line formation problem, focussing on the C I 156.1 nm and 165.7 nm lines, based on the VAL3C semi-empirical model (Vernazza et al. 1981). The authors found that the upper levels of these transitions are mostly populated by radiative recombination to highly excited levels, followed by radiative cascading. The central reversals in the calculated lines were deeper than in the observations. This could be due to only including four levels with higher excitation potential than the upper levels of the studied transitions, thus underestimating the radiative recombination, or it could be due to an underestimate of the radiative ionization of C I by hydrogen transitions.

Another theoretical modeling of the non local-thermodynamic-equilibrium (non-LTE) neutral carbon spectral-line formation was made by Fabbian et al. (2006) for stellar abundance analysis. In their study, they focussed on C I lines in the wavelength range of 830–960 nm. These lines are located both in the singlet and the triplet system of C I. The authors found that radiative processes dominate over collisional processes and the non-LTE effects are rather large. In metal-poor stars, inter system collisions between the singlet and the triplet systems may also be important. For this reason, Fabbian et al. (2006) also included inter system collisions with hydrogen, following the Drawin recipe (Drawin 1968, 1969) with a scaling factor. They found that the resulting non-LTE corrections to abundance determinations using these C I lines were not very dependent on the neutral hydrogen collisions.

Avrett & Loeser (2008) solve the non-LTE problem employing an extended C I–C IV model atom with 128 individual energy levels of C I grouped into 19 reference levels. This is done together with non-LTE computations of hydrogen (15 bound levels), O I–O VI (40 levels of O I grouped into 20 reference levels), and 10 other atoms and ions. They produce a semi-empirical model of the quiet solar chromosphere and transition region that reproduces as closely as possible the detailed spectrum observed by SUMER (Curdt et al. 2001) with an additional constraint that the transition region is given by an energy equation containing radiative processes, conduction, and particle diffusion (in contrast with the VAL3C model—Vernazza et al. 1981—where the
transition region temperature structure was a fitting function as well).

In this work, we will study the formation of the C I 135.58 nm line in the solar chromosphere employing both a 1D semi-empirical model and a 3D radiation-magnetohydrodynamic (RMHD) model. We will also explore the diagnostic potential of combining the observations in the C I and O I lines. In Section 2, we describe our model atmospheres, radiative transfer computations, and atomic models. In Section 3.1, we discuss the basic formation mechanism and the effects from the hydrogen solution. Following that, we discuss how the dynamics in the atmosphere influences the formation mechanism in Section 3.2 and we present synthetic spectra calculated based on 3D realistic atmospheres. In Section 4, we present their potential diagnostic value, and we conclude in Section 5.

2. Methods

2.1. Radiative Transfer Computations

In this study, we use the RH code (Uitenbroek 2001) to solve the non-LTE radiative transfer problem. RH is a multilevel accelerated lambda iteration code for radiative transfer calculations including PRD. It treats line blending self-consistently. We use the original RH 1D version to study the basic formation mechanism in Section 3.1 with the FALC (Fontenla et al. 1993) atmosphere.

For the 3D atmosphere, we use the 1.5D version of RH (Pereira & Uitenbroek 2015), which treats each column in a 3D atmosphere as an independent plane-parallel atmosphere. The advantage of this version of RH over the original version is that the code is parallelized using the Message Passing Interface such that the different columns can be calculated simultaneously. To save computational effort, we do not solve for hydrogen and carbon simultaneously but solve first for hydrogen and store the radiation fields to be used for the carbon solution.

In order to do so accurately, we modified RH so that it stores the ratio between the emissivity and absorption coefficients ($g_{ij}$ in Equation (26) of Uitenbroek 2001) for Lyα in the hydrogen calculation. The code then reads these ratios in the computation for carbon and so includes the correct radiation field including PRD effects for the radiative pumping by Lyα in the C I continuum (see Section 3.1).

For the hydrogen computation, we also modified RH to maintain the non-equilibrium hydrogen ionization degree as present in the 3D model atmosphere (see Section 2.2). We keep the proton density fixed and remove the rate equation for the continuum to keep the rate equations internally consistent. This method is a fairly accurate approximation of the full non-equilibrium non-LTE radiative transfer because the timescales for the ionization balance are long, but the excited levels of hydrogen adapt very fast and can thus be treated assuming statistical equilibrium. For further details, we refer the reader to Golding et al. (2017), who discuss this method in the context of helium.

In Section 4, we also make use of non-LTE calculations of the O I 135.56 nm line presented in Lin & Carlsson (2015).

2.2. Model Atmospheres

In this study, we use two model atmospheres. In Section 3.1, we use the semi-empirical solar chromosphere model FALC (Fontenla et al. 1993) to study the basic formation mechanism. The FALC model is a semi-empirical atmosphere model that describes the atmosphere in an averaged fashion without dynamics, hence is suitable for studying the line formation qualitatively. However, the nature of the solar chromosphere is far from static. To study the radiation from such a dynamic system, we need a more realistic atmosphere model than FALC. We chose to use a model computed with the RMHD code Bifrost (Gudiksen et al. 2011). In Section 3.2, we use a snapshot from the publicly available 3D simulation en024048_hion (Carlsson et al. 2016). The snapshot extends $24 \times 24 \times 16.8 \text{ Mm}$ in physical space, mapped onto a grid of $504 \times 504 \times 496$ cells. It covers the upper convection zone, the chromosphere, the transition region and the lower corona and includes a large-scale magnetic field with two polarities separated by about $8 \text{ Mm}$ with an average unsigned magnetic field strength in the photosphere of $50 \, \text{G}$.

This particular snapshot has also been used in the study of the line formations of Hα (Leenaarts et al. 2012), Mg II h and k (Leenaarts et al. 2013a, 2013b; Pereira et al. 2013), C II 133.5 nm multiplet (Rathore & Carlsson 2015; Rathore et al. 2015a), and the O I 135.56 nm line (Lin & Carlsson 2015). We refer the reader to Carlsson et al. (2016) for more details on this simulation. We stress here that the purpose of the current work is to investigate the diagnostic potential of the C I 135.58 nm line and not to test the realism of the atmospheric model. It is well known that the employed Bifrost model fails to reproduce observations in several aspects, e.g., chromospheric lines are too narrow in the model on average and several emission lines are too weak. These discrepancies may be due to a lack of numerical resolution in the models or a lack of physical processes like ambipolar diffusion (e.g., Martínez-Sykora et al. 2017). However, for our purposes, it is enough that the model atmosphere contains the proper parameter range (there are both wide lines and strong emission at locations in the simulation but not enough to reproduce the mean profiles).

2.3. Quintessential Model Atom

We start with a model atom containing 168 levels with atomic data taken from the HAOS-Diper package (Judge & Meisner 1994). We do not include hydrogen collisions since atomic data for these are highly uncertain and the study by Fabbian et al. (2006) indicates that they are not important. We simplify this model atom for our purposes. In the simplification procedure, we make sure that at each step we get the same intensity from the FALC model atmosphere in the C I 135.58 nm line but also in two other C I lines in the IRIS wavelength range at 135.43 nm and at 135.71 nm. Since the lines we focus on here are within the singlet system and do not have any direct coupling with the triplet system, we start by excluding all states in the triplet system except the ground states. We do still include the radiative recombination rates into the triplet system with the approach given in Lin & Carlsson (2015). The corresponding effective recombination coefficients are listed in Table 1. We then further simplify our model atom by merging levels, following the procedure described in Bard & Carlsson (2008). The term diagram of the final 26-level model atom is shown in Figure 1 and the corresponding atomic parameters are listed in Table 2. The word “merged” in the level designation means that the level is such a merged super level. The level designation comes from the level with the lowest energy among the merged levels.
rangement of the 26-level CI model atom we use in this study. The energies and designations of each numbered level are listed in Table 2. The energies of the levels of the term 2s^2 2p^2 3P (levels 0, 1, 2) are very close to each other and the energy differences within the term are exaggerated in this diagram. The same is true for energy levels 14, 17 and 21, 22. Only the transitions within the IRIS wavelength range are shown in the diagram with vacuum wavelengths in nm and the transition of special interest here, the C I 135.58 nm line, in red.

![Figure 1](image)

**Figure 1**. Term diagram of the 26-level CI model atom we use in this study. The energies and designations of each numbered level are listed in Table 2. The energies of the levels of the term 2s^2 2p^2 3P (levels 0, 1, 2) are very close to each other and the energy differences within the term are exaggerated in this diagram. The same is true for energy levels 14, 17 and 21, 22. Only the transitions within the IRIS wavelength range are shown in the diagram with vacuum wavelengths in nm and the transition of special interest here, the C I 135.58 nm line, in red.

| Level | Energy (cm^{-1}) | Designation |
|-------|------------------|-------------|
| 0     | 0.000            | CI 2s^2 2p^2 3P_0 |
| 1     | 16.400           | CI 2s^2 2p^2 3P_1 |
| 2     | 43.400           | CI 2s^2 2p^2 3P_2 |
| 3     | 10192.630        | CI 2s^2 2p^2 3D_3 |
| 4     | 21648.010        | CI 2s^2 2p^2 3D_4 |
| 5     | 33735.200        | CI 2s^2 2p^2 3S_1 |
| 6     | 61981.820        | CI 2s^2 2p^3 1P_0 |
| 7     | 68856.330        | CI 2s^2 2p^3 1P_1 |
| 8     | 72838.251        | CI 2s^2 2p^3 1D_2-merged |
| 9     | 78532.462        | CI 2s^2 2p^4 1F^o-merged |
| 10    | 80562.850        | CI 2s^2 2p^4 1P_1 |
| 11    | 81769.790        | CI 2s^2 2p^4 1D_2 |
| 12    | 82251.710        | CI 2s^2 2p^4 1S_0 |
| 13    | 83497.620        | CI 2s^2 2p^4 1D^o_2 |
| 14    | 83877.310        | CI 2s^2 2p^5 3P_0 |
| 15    | 83947.430        | CI 2s^2 2p^4 1F^o_3 |
| 16    | 83997.906        | CI 2s^2 2p^4 1F^o_2-merged |
| 17    | 84032.150        | CI 2s^2 2p^4 1P^o_1 |
| 18    | 84851.530        | CI 2s^2 2p^5 3P_1 |
| 19    | 85399.810        | CI 2s^2 2p^5 3P_2 |
| 20    | 85717.731        | CI 2s^2 2p^5 3F^o_5-merged |
| 21    | 86909.475        | CI 2s^2 2p^4 3D^o-merged |
| 22    | 87083.365        | CI 2s^2 2p^3 3D^o_2-merged |
| 23    | 88260.370        | CI 2s^2 2p^3 3P_2 |
| 24    | 88856.030        | CI 2s^2 2p^3 3S^-merged |
| 25    | 90859.558        | CI 2s^2 2p^-3P_0 |

**Table 2**

| Level | Designation |
|-------|-------------|
| 21    | Transition from the ground term 2s^2 2p^2 3P to all excited states, followed by radiative cascading. |
| 22    | Transition from the ground term 2s^2 2p^2 3P to all excited states, followed by radiative cascading. |
| 23    | Transition from the ground term 2s^2 2p^2 3P to all excited states, followed by radiative cascading. |
| 24    | Transition from the ground term 2s^2 2p^2 3P to all excited states, followed by radiative cascading. |
| 25    | Transition from the ground term 2s^2 2p^2 3P to all excited states, followed by radiative cascading. |

3. Basic Formation Mechanism

3.1. Ionization Chain and the Line Formation

The main ionization process of CI is through photoionization from the 2s^2 2p^2 3P_1, 2s^2 2p^2 3P_2, and 2s^2 2p^2 3P_0 states with photoionization from the 2s^2 2p^2 3D_2 state being dominant. 2s^2 2p^2 3D_2 is also the lower state of the C I 135.58 nm line and it is mainly populated from the ground term 2s^2 2p^2 3P by collisions. The C II ground state is depopulated through radiative recombination to all excited states, followed by radiative cascading.

The upper state of the C I 135.58 nm line, 2s^2 2p^4 3F^o_3, is populated by radiative recombination from the continuum, and depopulated mostly to the state 2s^2 2p^4 1D_2. The C I 135.58 nm line (2s^2 2p^4 3F^o_3 – 2s^2 2p^2 3D_2), is, however, not the dominant channel of depopulating 2s^2 2p^4 3F^o_3.

The net rates for the 2s^2 2p^4 3F^o_3 and 2s^2 2p^2 1D_2 levels are shown in Figures 2 and 3, respectively.

The net-rate analysis shows that the ionization degree of neutral carbon is set by photoionization/radiative recombination.
and is therefore sensitive to the radiation field. Photoionization from the $2s^22p^2\,^1D_2$ level requires photons with wavelength below 123.96 nm. This photoionization edge is just long-ward of the hydrogen Ly$\alpha$ line at 121.2 nm and the photoionization rate is therefore sensitive to the Ly$\alpha$ intensity (Lites & Cook 1979). Although the Ly$\alpha$ intensity is highest close to the line core, for the integrated photoionization rate, its wide wings are important. Therefore, the treatment of the frequency redistribution of photons in Ly$\alpha$ is important. Assuming complete frequency redistribution (CRD) leads to an overestimate of the wing intensities, and therefore also of the photoionization rate, compared with the proper treatment with partial frequency redistribution (PRD, see Figure 4.)

We quantify this by defining the following ratio $R$ of photoionization rates:

$$R \equiv \frac{\int_{\nu_0}^{\infty} \sigma^\nu J_\nu (\text{PRD/CRD}) \, d\nu}{\int_{\nu_0}^{\infty} \sigma^\nu J_\nu (\text{No Ly}\alpha) \, d\nu}, \quad (1)$$

where $\sigma^\nu$ is the photoionization cross-section from the $2s^22p^2\,^1D_2$ level to the continuum, $J_\nu$ (CRD/PRD) is the radiation field with hydrogen lines in CRD/PRD, respectively, and $J_\nu$ (No Ly$\alpha$) is the radiation field without Ly$\alpha$ emission. This ratio thus quantifies the effect of the Ly$\alpha$ line on the photoionization of C. We show $R$ as a function of height in the FALC model in Figure 5. It is unity in the deep atmosphere but becomes larger above 0.5 Mm height. With the assumption of CRD in the Ly$\alpha$ line, the ratio becomes much larger than when assuming PRD owing to the extended Ly$\alpha$ wings in CRD.

Finally, we compare the O I 135.56 nm and the C I 135.58 nm lines that are calculated based on treating Ly$\alpha$ in PRD, CRD, and excluding the line altogether in Figure 6.

There are substantial differences in the resulting C I 135.58 nm line. The stronger the C I photoionization the stronger the line, which is consistent with the result that the upper level of the line is populated mainly through photorecombinations from C II.

To summarize the basic formation mechanism of the C I 135.58 nm line, we show the dominant channels of the C I formation in Figure 7.
3.2. Line Formation in a Dynamic Atmosphere

So far, we have studied the basic line-formation mechanisms using the 1D, static, semi-empirical model atmosphere FALC. We now turn to how the C I 135.58 nm line is formed in a more realistic atmosphere with velocity fields. For this purpose, we use the Bifrost simulation en024046_hion (Carlsson et al. 2016). To illustrate the line formation, we use the four-panel diagrams introduced by Carlsson & Stein (1997).

The vertically emergent intensity in a 1D plane-parallel semi-infinite atmosphere can be written as

$$I_\nu = \int_0^\infty S_\nu(z) e^{-\tau_\nu(z)} \chi_\nu(z) \, dz,$$

where $S_\nu$, $\chi_\nu$, and $\tau_\nu$ are the source function, opacity, and optical depth, respectively.

In this equation, the integrand describes the local creation of photons ($S_\nu(z)\,dz$) and the fraction of the those that escape ($e^{-\tau_\nu(z)}$), and the integrand is thus a natural definition of the contribution function to intensity on a height scale:

$$C_\nu(z) = S_\nu(z) e^{-\tau_\nu(z)} \chi_\nu(z).$$

We can rewrite this contribution function as

$$C_\nu(z) = S_\nu(z) \tau_\nu(z) e^{-\tau_\nu(z)} \frac{\chi_\nu(z)}{\tau_\nu(z)},$$

where the term $\tau_\nu(z) e^{-\tau_\nu(z)}$ peaking at $\tau_\nu = 1$ represents the Eddington–Barbier part of the contribution function, $S_\nu(z)$ gives the source function contribution and $\chi_\nu(z)/\tau_\nu(z)$ picks out effects of velocity gradients in the atmosphere (see Carlsson & Stein 1997).

Figure 8 shows the intensity formation of the C I 135.58 nm line in an atmospheric column with moderate velocities and almost no velocity gradients. The intensity is formed close to $\tau_\nu = 1$ as indicated by the maximum of the contribution function following the $\tau_\nu = 1$ curve. The continuum is formed at a height of 0.73 Mm, where the temperature is 3 kK but with a decoupled source function at a radiation temperature of 3.7 kK. The line core has optical depth unity at $z = 1.35$ Mm. The upper right panel shows that the source function increases up to $z = 1.2$ Mm and decreases higher up. The local maximum of the source function is the reason for the two emission peaks and the central reversal.

Figure 9 shows the intensity formation at another column in the atmosphere where the velocities are larger and there are significant velocity gradients in the line forming region. The intensity profile (shown in the lower right panel) still has two peaks and a central reversal but the reason is different from the case shown in Figure 8. The source function (upper right panel) is rather constant with height above $z = 1.5$ Mm, which would give a single peak intensity profile with a flat top. The reason we still get two emission peaks is that the velocity gradients around the velocity maxima at $z = 1.8$ Mm and $z = 1.6$ Mm give large $\chi_\nu/\tau_\nu$ terms (upper left panel).

A third example is given in Figure 10. At this column of the atmosphere, there is a strong velocity gradient above $z = 1.5$ Mm influencing both the $\tau_\nu = 1$ shape with its maximum height at a redshift of 4 km s$^{-1}$ and the intensity profile. The source function (the relevant one for the profile blueward of +4 km s$^{-1}$ is given by the blue line in the upper right panel) is slowly decreasing above $z = 1.4$ Mm but the $\chi_\nu/\tau_\nu$ term decreases with increasing redshift, so we get a maximum intensity at a redshift of 1 km s$^{-1}$.

From the selected cases shown above, we learn that the line profile is influenced both by the run of the source function with height and by velocity gradients in the atmosphere.

4. Diagnostic Potential

Spectral line-profiles encode information from the conditions in the atmosphere where the photons escape. To decode this information, we need to find the line-forming region and then
correlate observable quantities with atmospheric parameters in this region. We start this section with a discussion of the line-forming region.

4.1. The Line Core

As we have seen in the previous section, the C I 135.58 nm line has a typical optically thick line-formation with the contribution function to intensity centered around monochromatic optical depth unity. The maximum height we can get information from is at the wavelength where this optical depth unity is the highest. This wavelength is not immediately available observationally. In the absence of velocity fields, we have the maximum opacity at the rest wavelength of the transition, which is also the wavelength of maximum optical-depth-unity height. If the source function is monotonically increasing with height, we get an emission line with the maximum intensity at this wavelength. If there is a local maximum in the source function below the optical-depth-unity height at line center, we get an emission line with a self-reversal. Dependent on the source function variation with height, we may also get more than two peaks in the intensity profile. In the absence of velocity fields, the line center is at the position of the central emission maximum for profiles with an odd number of peaks and at the position of the central emission minimum for profiles with an even number of peaks. We use this wavelength as our observationally defined line-core wavelength in spite of the fact that, as we have seen in
Section 3.2, velocity gradients may strongly affect the contribution function to intensity and the correlation between this observationally defined line core wavelength and the wavelength of maximum \( \tau_v, 1 \) height.

In the following, we inspect various quantities at this wavelength.

### 4.2. The Contribution Function

In Figure 11, we show the contribution function to intensity at the line-core wavelength (as defined in Section 4.1) along a selected cut at \( x = 12 \text{ Mm} \) in Figure 12. The red line in Figure 11 represents the \( \tau_v, 1 \) height. It is clear that the maximum of the contribution function to intensity is tightly correlated with this height, consistent with an optically thick formation of the line.

### 4.3. Formation Height

As the C I line has an optically thick formation, the \( \tau_v = 1 \) height could be a natural choice for its formation height. However, to be consistent with the treatment with the O I 135.56 nm line (Lin & Carlsson 2015), we follow the same definition for the C I 135.58 nm line and use the contribution-function-weighted averages to define the formation height and other quantities:

\[
X_{th} = \frac{\int_0^\infty C_i(z) X(z)\,dz}{\int_0^\infty C_i(z)\,dz},
\]

where \( X \) is the quantity under consideration and \( X_{th} \) is its contribution-function-weighted average.

The result for the contribution-function-weighted C I 135.58 nm line-formation height is shown in Figure 12. The loop-like features show the influence of the magnetic structures on the line opacity. At some points, the formation height is very much lower than at neighboring points (seen as darker small patches, also visible along the selected cut shown in Figure 11). These deviating formation heights are associated with the algorithm for selecting the line core wavelength not finding the actual wavelength of the maximum \( \tau_v = 1 \) height.

### 4.4. Velocity

With the line-core frequency defined in Section 4.1, we can obtain the Doppler shift with respect to the rest frequency and compare with the contribution-function-weighted vertical velocity. In Figure 13, we find the correlation to be quite tight, making C I 135.58 nm line a good velocity diagnostic.

### 4.5. Electron Density

It is interesting to investigate the diagnostic power of the O I 135.56 nm line and the C I 135.58 nm line combined, because they are observed together with IRIS.

As discussed in Lin & Carlsson (2015), the O I 135.56 nm line intensity is proportional to the square of the electron density: the line is formed by recombination from O II followed by radiative cascading to the upper level of the transition. The recombination rate scales linearly with the electron density. The O II density is proportional to the proton density (and hence the electron density), which combined yields the quadratic dependence.

In Section 3.1, we show that the C I 135.58 nm line formation is driven by ionization by \( \text{Ly}\alpha \) photons followed by radiative recombinations. Such a process scales linearly with the electron density (through the recombination) but of course will also be dependent on the \( \text{Ly}\alpha \) radiation field. As a result, we anticipate that the C I/O I line ratio scales as \( \sim J(\text{Ly}\alpha)/N_e \), where \( J(\text{Ly}\alpha) \) is the radiation field in the \( \text{Ly}\alpha \) transition. In Figure 14, we show the correlation between the electron density at the average formation height and the C I/O I line ratio. It shows a roughly linear correlation, but with a considerable spread.
4.6. Formation Height Difference

From the histogram of the formation heights of the O I 135.56 nm line and the C I 135.58 nm line (Figure 15), it is clear that these two lines map slightly different layers in the atmosphere. In general, the C I 135.58 nm line forms higher than the O I 135.56 nm line. The distribution of the C I 135.58 nm line peaks around 1.5 Mm, while the O I 135.56 nm line distribution peaks around 1.2 Mm.

The two lines have different sensitivity to the electron density (see Figure 14). This also means that there is a correlation between the C I/O I line-core intensity ratio and the formation height difference—a low intensity ratio corresponds to a high intensity oxygen line formed low down and thus with a large formation height difference. This correlation is shown in Figure 16. The correlation is clear but the spread is rather large.

4.7. The Velocity Difference and the Velocity Gradient

Because the O I 135.56 nm line and the C I 135.58 nm line probe slightly different layers in the atmosphere and their
Doppler shifts are good velocity indicators, it is possible to take the difference between their individual Doppler shifts and measure the velocity difference between these two layers. In Figure 17, we show the correlation between the difference between the contribution-function-weighted velocities of the lines and the difference of their individual Doppler shifts. The correlation is strong. Together with the correlation between the line ratio and the formation height difference (Figure 16), it is possible to derive a rough estimate of the velocity gradient in the middle chromosphere.

5. Discussion and Conclusions

We presented an analysis of the formation of the \textsc{C}I 135.58 nm line in the FALC 1D semi-empirical atmosphere model and a 3D RMHD model computed with the Bifrost code. We show that the line has a typical optically thick line formation.

The \textsc{C}I/\textsc{C}II ionization balance is mainly driven by photoionization from $2s^22p^2\,^1D_2$, with the radiation field in \textsc{Ly}$\alpha$ playing a central role. Proper modeling of the \textsc{C}I 135.58 nm line should therefore incorporate non-LTE modeling of hydrogen including PRD in the \textsc{Ly}$\alpha$ line. In a static atmosphere, the line core usually appears with a central reversal, due to a local maximum of the source function below the maximum $\tau_v = 1$ height. However, if velocity gradients are present in the atmosphere then the line profiles can have more different, usually asymmetric, shapes. Interestingly, we find some instances where a strong velocity gradient close to the line-core formation height can cause a single-peaked profile in spite of a source function decreasing with height at the maximum $\tau_v1$ height (which would lead to a central reversal in the absence of the velocity gradient). We also find cases of the opposite: velocity gradients leading to a central reversal even though the source function monotonically increases with height.

The Doppler shift of the line core is a good velocity diagnostic.

The \textsc{C}I 135.58 nm line can be combined with the nearby \textsc{O}I 135.56 nm line for increased diagnostic power. The \textsc{C}I 135.58 nm line typically forms slightly higher than the \textsc{O}I 135.56 nm line, and both are good velocity diagnostics. The difference in their Doppler shifts is therefore a good indicator of the velocity difference between their formation layers. By combining this with the correlation of the \textsc{C}I/\textsc{O}I line ratio and the formation height difference, one can derive an estimate of the actual velocity gradient. Because the line ratio–height difference correlation is weak and has considerable spread, this estimate is, however, rather coarse.

Furthermore, we find that the \textsc{C}I/\textsc{O}I total line intensity ratio is inversely proportional to the electron density: $(I(\textsc{C}I))/(I(\textsc{O}I)) \sim 1/N_e$, but again with a large spread in the correlation.

We stress that these relations have been derived from a Bifrost model snapshot that is typical of the quiet Sun. A flare (where the \textsc{C}I 135.58 nm line is often stronger than the \textsc{O}I 135.56 nm line) has very different atmospheric properties and the relations derived here cannot be used under such conditions.

We also note that all correlations are derived from radiative transfer calculations using the 1.5D approximation. The \textsc{Ly}$\alpha$ line is, however, strongly influenced by 3D effects (Stépán et al. 2015; Sukhorukov & Leenaarts 2017), and this might have an influence on the results presented here.

ORCID iDs

Mats Carlsson @ https://orcid.org/0000-0001-9218-3139
Jorrit Leenaarts @ https://orcid.org/0000-0003-4936-4211

References

Avrett, E. H., & Loeser, R. 2008, ApJS, 175, 229
Bard, S., & Carlsson, M. 2008, ApJ, 682, 1376
Carlsson, M., Hansteen, V. H., Gudiksen, B. V., Leenaarts, J., & De Pontieu, B. 2016, A&A, 585, A4
Carlsson, M., & Stein, R. F. 1997, ApJ, 481, 500
Cheng, C. C., Feldman, U., & Doschek, G. A. 1980, A&A, 86, 377
Curdt, W., Brekke, P., Feldman, U., et al. 2001, A&A, 375, 591
Dravins, H.-W. 1968, ZPhys, 211, 404
Dravins, H. W. 1969, ZPhys, 225, 483
Fabbian, D., Asplund, M., Carlsson, M., & Kiselman, D. 2006, A&A, 458, 899
Fontenla, J. M., Avrett, E. H., & Loeser, F. 1993, ApJ, 406, 319
Golding, T. P., Leenaarts, J., & Carlsson, M. 2017, A&A, 597, A102
Gudiksen, B. V., Carlsson, M., Hansteen, V. H., et al. 2011, A&A, 531, A154
Judge, P. G., & Meisner, R. W. 1994, in ESA Special Publication, 373, Solar Dynamic Phenomena and Solar Wind Consequences, the Third SOHO Workshop, ed. J. J. Hunt (ESA: Paris), 67
Leenaarts, J., Carlsson, M., & Rouppe van der Voort, L. 2012, ApJ, 749, 136
Leenaarts, J., Pereira, T. M. D., Carlsson, M., Uitenbroek, H., & De Pontieu, B. 2013a, ApJ, 772, 89
Leenaarts, J., Pereira, T. M. D., Carlsson, M., Uitenbroek, H., & De Pontieu, B. 2013b, ApJ, 772, 90
Lin, H.-H., & Carlsson, M. 2015, ApJ, 813, 34
Lites, B. W., & Cook, J. W. 1979, ApJ, 228, 598
Martínez-Sykora, J., De Pontieu, B., Hansteen, V. H., et al. 2017, Sci, 356, 1269
Mauas, P. J., Avrett, E. H., & Loeser, R. 1989, ApJ, 345, 1104
Pereira, T. M. D., Leenaarts, J., De Pontieu, B., Carlsson, M., & Uitenbroek, H. 2013, ApJ, 778, 143
Pereira, T. M. D., & Uitenbroek, H. 2015, A&A, 574, A3
Rathore, B., & Carlsson, M. 2015, ApJ, 811, 80
Rathore, B., Carlsson, M., Leenaarts, J., & De Pontieu, B. 2015a, ApJ, 811, 81
Rathore, B., Pereira, T., Carlsson, M., & De Pontieu, B. 2015b, ApJ, 814, 70
Sukhorukov, A. V., & Leenaarts, J. 2017, A&A, 597, A46
Uitenbroek, H. 2001, ApJ, 557, 389
Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, ApJS, 45, 635
Štěpán, J., Trujillo Bueno, J., Leenaarts, J., & Carlsson, M. 2015, ApJ, 803, 65