

## **Dark off-limb gap: manifestation of temperature minimum and dynamic nature of the chromosphere**

DAVID KURIDZE,<sup>1,2</sup> PETR HEINZEL,<sup>3,4</sup> JÚLIUS KOZA,<sup>5</sup> AND RAMON OLIVER<sup>6,7</sup>

<sup>1</sup>*Department of Physics, Aberystwyth University, Ceredigion, SY23 3BZ, UK*

<sup>2</sup>*Abastumani Astrophysical Observatory, Mount Kanobili, 0301, Abastumani, Georgia*

<sup>3</sup>*Astronomical Institute, The Czech Academy of Sciences, 25165 Ondřejov, Czech Republic*

<sup>4</sup>*University of Wrocław, Centre of Scientific Excellence - Solar and Stellar Activity, Kopernika 11, 51-622 Wrocław, Poland*

<sup>5</sup>*Astronomical Institute, Slovak Academy of Sciences, 059 60 Tatranská Lomnica, Slovakia*

<sup>6</sup>*Departament de Física, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain*

<sup>7</sup>*Institute of Applied Computing & Community Code (IAC3), UIB, Spain*

Submitted to ApJ

### ABSTRACT

We study off-limb emission of the lower solar atmosphere using high-resolution imaging spectroscopy in the  $H\beta$  and Ca II 8542 Å lines obtained with the CHROMospheric Imaging Spectrometer (CHROMIS) and the CRisp Imaging SpectroPolarimeter (CRISP) on the Swedish 1-m Solar Telescope. The  $H\beta$  line wing images show the dark intensity gap between the photospheric limb and chromosphere which is absent in the Ca II images. We calculate synthetic spectra of the off-limb emissions with the RH code in the one-dimension spherical geometry and find good agreement with the observations. The analysis of synthetic line profiles shows that the gap in the  $H\beta$  line wing images maps the temperature minimum region between the photosphere and chromosphere due to the well known opacity and emissivity gap of Balmer lines in this layer. However, observed gap is detected farther from the line core in the outer line wing positions than in the synthetic profiles. We found that an increased microturbulence in the model chromosphere is needed to reproduce the dark gap in the outer line wing, suggesting that observed  $H\beta$  gap is the manifestation of the temperature minimum and the dynamic nature of the solar chromosphere. The temperature minimum produces a small enhancement in synthetic Ca II line-wing intensities. Observed off-limb Ca II line-wing emissions show similar enhancement below temperature minimum layer near the edge of the photospheric limb.

*Keywords:* Solar chromosphere (1479) — Spectroscopy (1558) — Radiative transfer simulations (1967)

### 1. INTRODUCTION

The solar atmosphere under non-ideal MHD approximation evolves as a magnetized fluid that is governed by equations of hydrodynamics representing conservation of mass, momentum, and energy. These are coupled with radiative transfer equation and induction equation for magnetic field. Within the three-dimensional radiation-MHD (3D R-MHD) modeling, basic parameters of the solar atmosphere such as temperature, ve-

locity, density, and magnetic field result from solving them in spatial and temporal domain. However, the 3D R-MHD modeling has limitations, such as ad-hoc replacing the viscosity and resistance by numerical terms that are independent of temperature (Leenaarts 2020). One of the most puzzling aspects of the solar atmosphere is breaking the radiative equilibrium in the layers above the photosphere. Therefore deposition of non-thermal energy and conversion into heat must occur in the chromosphere and corona—thus they are hotter than the radiative equilibrium assumes. The question “How much hotter?” was answered by analysis of ground and space spectroscopic data acquired by various techniques.

Early solar physics utilized solar eclipses as the primary source of quantitative chromospheric data (see Judge et al. 2019, and references therein). Time series of flash spectra, acquired with high cadence in brief moments after and before the second and third contact, respectively, yielded first hints on physical conditions in the chromosphere. For example, an extensive set of the high-cadence chromospheric flash spectra, obtained at the 1952 eclipse in Khartoum, was analyzed in Athay et al. (1954). Recently, high-cadence flash spectra ( $\geq 8$  ms cadence), acquired by a novel experiment during the 2017 August 21 eclipse, were studied in Judge et al. (2019).

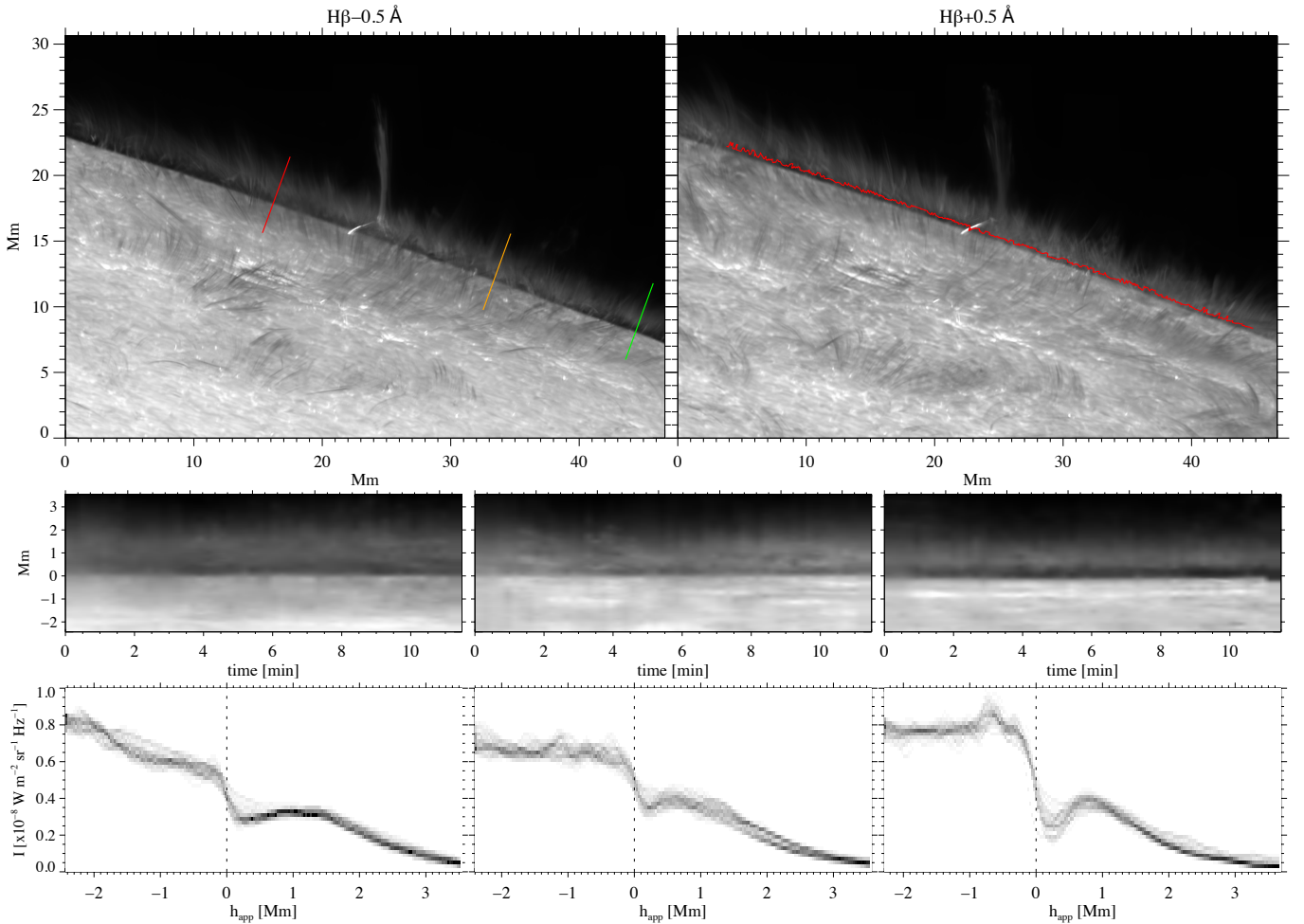
Lack of detailed knowledge of heating mechanisms in the layers, where radiative equilibrium breaks down, forced to construct one-dimensional (1D) semi-empirical (SE) models where the temperature structure of the atmosphere (i.e.,  $T$  versus the column mass or height) is inferred from long-slit spectroscopy by the radiative transfer calculations assuming non-local thermodynamic equilibrium (non-LTE; i.e., departures from LTE). The non-LTE problem takes consistently into account weak coupling of radiation field with the matter in the chromosphere. The 1D SE models are primarily based on on-disk observations of continua and several strong spectral lines. Temperature is the variable that most strongly controls the continuum and spectral line shapes and intensities yielded by the classical SE models (Gingerich et al. 1971; Vernazza et al. 1981; Fontenla et al. 1993; Rutten & Uitenbroek 2012; Heinzel & Štěpán 2019). This sensitivity arises from the exponential and power dependence with  $T$  in the excitation-ionization processes (Gray 2008). Their characteristic feature is a distinct temperature minimum (TM) separating the upper photosphere, dominated by the gas pressure, from the lower chromosphere where the magnetic field gains a dominance over the gas. Unfortunately, many underlying processes, such as granulation, waves, flows, and jets, are not reproduced by 1D SE models as they are obtained using the hydrostatic equilibrium and plane-parallel geometry approximation (Rutten 2002). These processes are better represented by computationally much more expensive 3D-MHD models which also have limitations mentioned in the first paragraph of this section. This may justify an employment of 1D modeling particularly when the challenging off-limb viewing geometry is considered.

It has been shown that specific monochromatic intensities of some chromospheric lines sample the TM layer and can be used to study the location and properties of this layer. For example, the  $K_1$  feature of Ca II K line can map the TM in the solar and stellar atmo-

spheres (e.g., Shine et al. 1975; Ayres & Linsky 1976; Avrett 1985; Mauas 2000). The most cited paper on SE non-LTE models by Vernazza et al. (1981) places the TM with the local temperature  $\sim 4200$  K about 500 km above the visible solar surface corresponding to the optical depth unity at  $5000 \text{ \AA}$ . Since then the temperature and the location of TM have been a subject of an intensive discussion. Fontenla et al. (2007) list previous papers preferring warm or cooler TM models, divided further as a single component or bifurcated, and present a single-component model, which matches several apparently contradictory observations. For example, SE models of sunspot by Maltby et al. (1986) place TM at the height of around 300 – 550 km. Analyzing the flare spectra of Ca II H and K lines Machado & Linsky (1975) showed that the TM in flares is hotter and formed deeper in the atmosphere than in quiet-Sun models. Similar results have been found by Kuridze et al. (2017) who constructed SE models of C-class flare employing high-resolution SST observations of the Ca II 8542  $\text{\AA}$  and non-LTE inversions.

Spectral diagnostics of thermal conditions near and above TM utilizes the strong vibration-rotation lines of monoxide carbon (CO) at  $4.6 \mu\text{m}$ . Remarkably, the solar CO spectra suggest the coexistence of a cool (less than 4000 K) component of the solar chromosphere with the hot, bright gas at 6000 to 7000 K. Large horizontal velocities are observed, implying that the cool component is sustained by the supersonic adiabatic expansion of upwelling gas in overshooting granules (Solanki et al. 1994). This motivated an introduction of the concepts of thermal bifurcation in the solar outer atmosphere (Ayres 1981) and the so-called COmosphere, a term coined by G. Wiedemann (Wiedemann et al. 1994; Ayres 2002). This zone probably consists of patchy clouds of cool gas, seen readily in off-limb emissions of CO lines, threaded by hot gas entrained in long-lived magnetic filaments as well as transient shock fronts (Ayres 2003, 2010). The COmosphere was not anticipated in classical 1D models of the solar outer atmosphere, but is quite at home in the contemporary 3D highly dynamic view (Wedemeyer et al. 2004).

The 3D R-MHD modeling confirms that the lower solar atmosphere has much more complex temperature structure where location of TM is not well-defined (Bjorgen et al. 2019, Figures 12–15). However, spatially averaged temperature structure of these models is still characterized with a single well-defined TM layer that can be assumed as a boundary between the photosphere and chromosphere. This raises the questions whether TM is a local, dynamic plasma parameter rather than a homogeneous global property of the atmosphere. Sur-



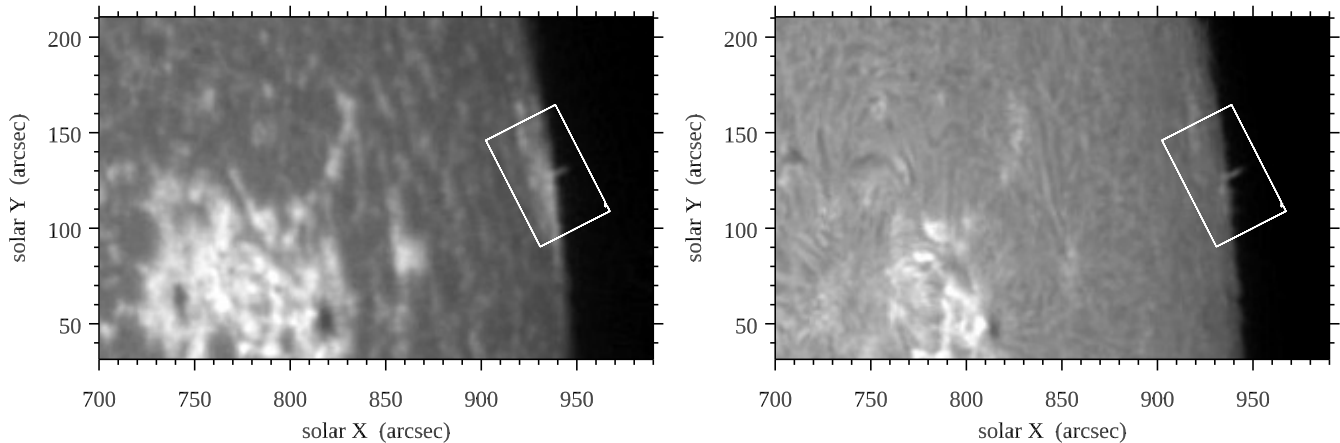
**Figure 1.** Top: CHROMIS  $H\beta$  wing images at  $\Delta\lambda = -0.5 \text{ \AA}$  (left) and  $+0.5 \text{ \AA}$  (right). The red contour in the top right panel follows the locations of minimum intensity in the dark gap. Middle: Time-distance diagrams of intensities extracted along the dashes in the top left panel. Bottom: Superimposition of the extracted intensities at individual times shown in the middle panels. The zero apparent height of the photospheric limb corresponds to the position of inflection point (the vertical dashed line) of the radial intensity gradients along the dashes pertinent to the  $H\beta$  far wing image at  $\Delta\lambda = -1.2 \text{ \AA}$ .

prisingly, Wedemeyer et al. (2004) concluded that TM and the upward oriented temperature gradient derived from semi-empirical models might be illusive in the sense that they do not really mean a rise of the average gas temperature with height.

One of the key aspects that controls the physical condition in which the emergent intensity forms in the lower atmosphere is the radiative coupling between the plasma and underlying radiation. The chromosphere is a highly non-LTE environment where radiation is weakly coupled to the local plasma condition. Furthermore, the lower atmosphere is highly structured by various processes (convection, jets, magnetic flux tubes, oscillations, waves) which appear as large and small scale perturbations of the plasma. Response of the the inhomogeneous, dynamic plasma to the underlying radiation defines the complex temperature structure of the atmo-

sphere which is manifested in high-resolution, state of the art models and observations. Therefore, transitional layer between photosphere and chromosphere can be introduced in terms of this interaction rather than simple position of TM. Chromosphere can be defined as a region where hydrogen stays predominantly neutral as a result of this complex interaction (Carlsson 2007).

Chromospheric off-limb observations offer a new view on the problem of TM in association with an off-limb feature called the intensity dark gap or the intensity dip introduced in Judge & Carlsson (2010). The wide-band off-limb filtergrams in the  $H\alpha$  center by Loughhead (1969), Nikolsky (1970), and Alissandrakis & Macris (1971) revealed the dark gap, referred to as the dark stripe and the dark band in the two latter papers, crowned with a shell of enhanced chromospheric emission. Loughhead (1969) suggested that the observed



**Figure 2.** ChroTel Ca II K (left) and H $\alpha$  (right) images, taken on 2018 June 22 at 08:34 UT, when the remnants of decaying AR NOAA 12714 at the limb display the jet at  $(x, y) = (940'', 130'')$ , which corresponds to the long spicule in the top panels of Figure 1 and in the left panel of Figure 4.

dark gap can be associated with the TM region of the solar atmosphere (Alissandrakis & Macris 1971).

Judge & Carlsson (2010) analyzed broadband Ca II H filtergrams of limb spicules obtained by the Hinode’s Solar Optical Telescope and pointed on a dip in the synthetic intensities which is not in qualitative disagreement with the dip in H $\alpha$  line center intensities discovered by Loughhead (1969). Because the relevant formulations by Judge & Carlsson (2010, Section 4.2) are very apt in this context we quote them literally: “The cores of H $\alpha$  and neutral helium lines routinely show a dip in intensity surrounded by a shell of emission (e.g., White 1963; Loughhead 1969; Pope & Schoolman 1975). However, dips seen in visible lines of hydrogen and helium may result more from the well-known lack of opacity in the low to mid chromosphere and extra opacity due to fibrils which appear to overarch the stratified chromosphere. Resolving the issue would require detailed calculations of H $\alpha$  and He lines with models taking into account the fibril structure and excitation mechanisms populating these excited atomic levels.” However, a few lines further they emphasize: “Importantly, we also note that our calculations never remove the off-limb dip entirely ... yet at least some of the Hinode BFI images appear to show no hint of a dip.”

The mentioned helium dip is well visible in the narrow-band filtergram in the He I D3 line center by Libbrecht (2016, page 60, Figure 4.5). The formation of the mid-chromospheric H $\alpha$  opacity gap is shown in Leenaarts et al. (2012). Recently, Pazira et al. (2017) have detected the dark gap in the O I 7772 Å line center with the narrow-band observations obtained with the CRisp Imaging SpectroPolarimeter (CRISP) on the Swedish Solar Telescope (SST). In concert with Judge & Carlsson (2010) they concluded that the dark gap is produced

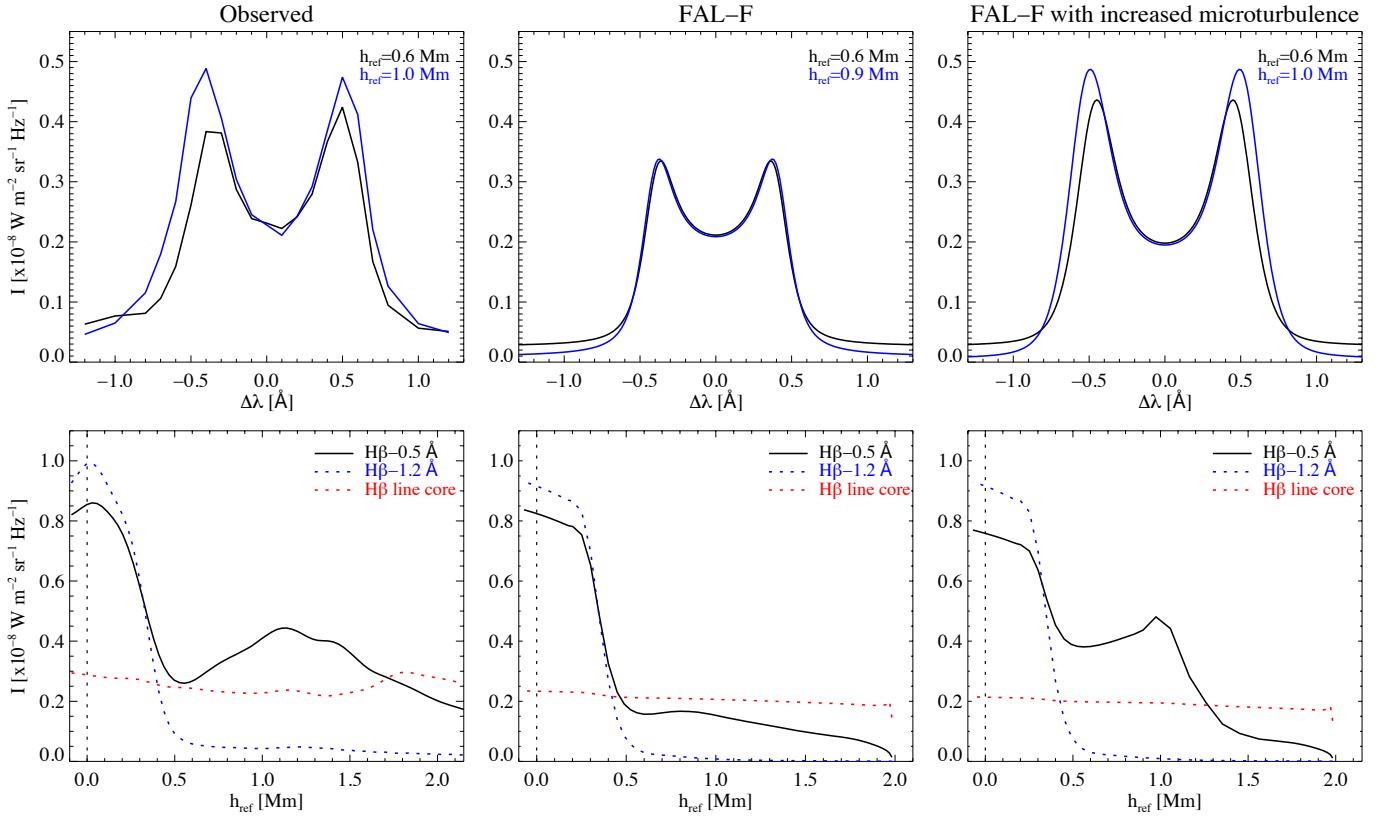
by height variations of the line opacity and corresponds to the TM layer.

This paper continues in the previous detection and modeling of dark gap but using high-resolution imaging spectroscopy data of the solar limb in the H $\beta$  and Ca II 8542 Å lines analyzing them by the radiative-transfer code RH by Uitenbroek (2001) in the one-dimension spherical geometry. We study the emergent intensities from different heights with respect to the photospheric limb and detect the dark gap between the photosphere and chromosphere in H $\beta$  line wing images. We analyze the line contribution functions of the synthetic spectra and their components to interpret spectral characteristics of the observed off-limb emissions including formation of dark gap.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. Observational setup

We observed the western limb of the Sun on 2018 June 22 between 08:20 and 08:43 UT near the active region NOAA 12714 (Figure 1). The observations were made with the CRISP (Scharmer 2006; Scharmer et al. 2008) and the CHROMIS (Löfdahl et al. 2021) instruments, both based on dual Fabry-Pérot interferometers mounted on the SST (Scharmer et al. 2003a,b). The CHROMIS observations include narrow-band spectral imaging in the H $\beta$  spectral line. The line profile scan consists of 21 profile samples ranging from  $-1.2 \text{ \AA}$  to  $+1.2 \text{ \AA}$  at positions  $\pm 1.2, \pm 1.0, \pm 0.8, \pm 0.7, \pm 0.6, \pm 0.5, \pm 0.4, \pm 0.3, \pm 0.2, \pm 0.1,$  and  $0.0 \text{ \AA}$  from the line center. CHROMIS data are processed using the CHROMISRED reduction pipeline (currently refereed to SSTRED), which includes MOMFBD image restoration and absolute intensity calibration (Löfdahl et al. 2021). The CRISP data comprises narrow-band imaging



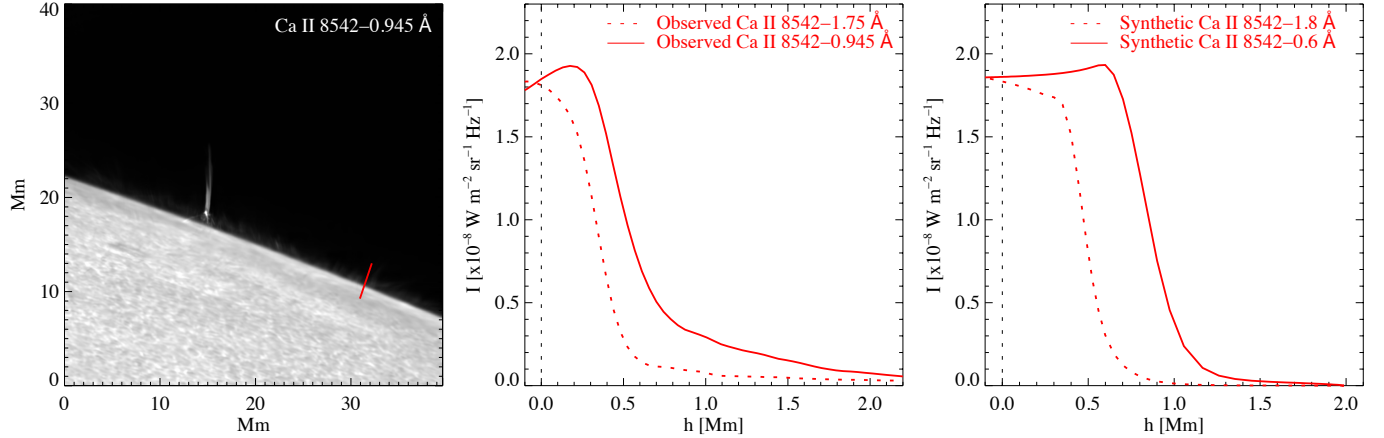
**Figure 3.** Top: Observed (left) and synthetic (middle and right) H $\beta$  line profiles in the dark gap at  $h_{\text{ref}} \sim 0.6$  Mm (black) and at the maximum of chromospheric emission at  $h_{\text{ref}} \sim 1$  Mm (blue). Bottom: Observed (left) and synthetic (middle and right) monochromatic intensities at indicated wavelength separations from the H $\beta$  line center. The left panels pertain to the green dash in the top left panel of Figure 1. The middle and right panels display the profiles for standard and increased microturbulence in the FAL-F model, respectively.

spectropolarimetry in the Ca II 8542 Å line profile sampled from  $-1.75$  Å to  $+1.75$  Å in 21 line positions  $\pm 1.75$ ,  $\pm 0.945$ ,  $\pm 0.735$ ,  $\pm 0.595$ ,  $\pm 0.455$ ,  $\pm 0.35$ ,  $\pm 0.21$ ,  $\pm 0.14$ ,  $\pm 0.07$ , and  $0.0$  Å from the line center (hereafter, unless specified otherwise, when referring to the Ca II line we mean the Ca II 8542 Å line). An acquisition time of each spectral scan of the Ca II line was 16 s but the cadence of the time series was 33 s due to interleaved spectropolarimetric scans in the Fe I 6302 Å line. More details on the observations and data can be found in Kuridze et al. (2021). In the following we employ data from the 13 min subinterval of the observational run lasting about 23 min.

Context imaging of the observed region in the Ca II K and H $\alpha$  filtergrams (Figure 2) are provided by the 10 cm robotic Chromospheric Telescope (ChroTel, Kentischer et al. 2008; Bethge et al. 2011), located at the Observatorio del Teide on Tenerife. ChroTel is a multi-wavelength imaging telescope for full-disk synoptic observations of the solar chromosphere in the Ca II K, H $\alpha$ , and He I 10830 Å lines.

## 2.2. Radiometric calibration and convolution

The comparison of SST data with outputs of radiative transfer computations requires careful intensity calibration of the former and convolution of the latter with the transmission profiles of the SST instruments provided by J. de la Cruz Rodríguez (2017, private communication) and M. Löfdahl (2019, private communication). Here we use the same CRISP data as in the paper by Kuridze et al. (2021) and its Section 2.2 “Data Radiometric Calibration” is also valid for this work. The processing pipeline yields the CHROMIS data implicitly calibrated in disk-center absolute intensity units using the Hamburg disk center spectral atlas as a reference (Neckel 1999), disregarding the actual position angle of CHROMIS science data (Löfdahl et al. 2021, Section 4.4). Therefore we perform recalibration of the CHROMIS data following the same procedure as at CRISP data but taking the H $\beta$  profiles from David (1961) as a calibration reference and the CHROMIS transmission profile provided by M. Löfdahl (2019, private communication). The resulting intensities expressed relative to the quiet-Sun continuum intensity at the disk center are converted to the absolute



**Figure 4.** CRISP Ca II 8542 Å blue wing image at  $\Delta\lambda = -0.945 \text{ \AA}$  (left). Observed monochromatic intensities along the red dash in the left panel (middle) and synthetic intensities (right).

intensities in the radiometric units  $\text{W m}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$  by the disk-center absolute continuum intensity taken from Cox (2000).

### 3. ANALYSES AND RESULTS

#### 3.1. Appearance of $H\beta$ dark gap

The top panels of Figure 1 show the western limb in the  $H\beta$  line wing images at  $\Delta\lambda = \pm 0.5 \text{ \AA}$  taken on 2018 June 22 at 08:34:24 UT. The SE model of the spicule in the center of the Field of View (FoV) is presented in Kuridze et al. (2021). This work is aimed at the off-limb emissions from the edge of photosphere up to the chromosphere. Both  $H\beta$  wing images suggest a presence of dark gap which closely follows the limb below the chromospheric canopy and the forest of type II spicules. To investigate the location of dark gap the intensities at different time moments are extracted along the three radial dashes of length 6 Mm shown in the top left panel of Figure 1. The length of these dashes is chosen to cross the limb, the dark gap, and the off-limb chromosphere at different parts of FoV. The time-distance diagrams along each dash (middle panels of Figure 1) and density diagrams produced by superposition of extracted intensities at different time moments (bottom panels of Figure 1) clearly confirm the existence of dark gap at the selected portions of FoV over most of the 13 min time span.

We define the observable photospheric limb in the  $H\beta$  imagery (hereafter as the apparent limb) as time-averaged positions of inflection points of the steepest intensity gradients along the dashes in the  $H\beta$  far wing image at  $\Delta\lambda = -1.2 \text{ \AA}$  (not shown). The position of the apparent limb defines the zero point of the spatial scales at  $x$  axes in the bottom panels of Figure 1. We will refer to the spatial scale as the apparent height denoted as  $h_{\text{app}}$ . However, the position of the observ-

able photospheric limb slightly varies possibly due to small-scale photospheric inhomogeneities producing local Wilson depressions. Therefore the apparent height of dark gap also slightly varies along the observable photospheric limb. It is shown in the top right panel of Figure 1 in which the red contour follows the positions of dark gap intensity minima yielding the average apparent height of  $0.265 \pm 0.055 \text{ Mm}$ . We take this value as the height of dark gap above the apparent limb.

We note that the apparent limb is uplifted by about 0.35 Mm above the level with the optical depth unity at 5000 Å viewed at the disk center. More details on the subject can be found in Athay (1976, pages 8–9, 279–280) and Lites (1983, Table 1). This off-set is due to an increase of optical depth at 5000 Å when moving LoS from disk center ( $\mu = 1$ ) to limb ( $\mu = 0$ ).

Example of the observed monochromatic intensities along the green dash are shown in the bottom left panel of Figure 3. Here we introduce the reference height  $h_{\text{ref}}$  shifted with respect to  $h_{\text{app}}$  as  $h_{\text{ref}} = h_{\text{app}} + 0.35 \text{ Mm}$ . It will be useful for later comparisons with the synthetic intensities computed by the RH code which will refer to the base of the photosphere ( $h_{\text{ref}} = 0$  in the bottom middle and right panel of Figure 3) with the optical depth unity at 5000 Å. Now the bottom left panel of Figure 3 shows the dark gap at  $\Delta\lambda = -0.5 \text{ \AA}$  at  $h_{\text{ref}} \sim 0.6 \text{ Mm}$  compared to  $h_{\text{app}} \sim 0.265 \text{ Mm}$  in the bottom panels of Figure 1. Remarkably, the  $H\beta$  line core intensity lacks any signature of dark gap compared to the previous  $H\alpha$ , He I D3, and O I 7772 Å detection referred to in Section 1. The top left panel of Figure 3 shows the  $H\beta$  line profiles at the dark gap at 0.6 Mm and at the point of Maximum Off-Limb Emission (hereafter as MOLE in the context of observed and synthetic intensities) outside the dark gap where the observed off-limb emission has its local maximum at the height 1 Mm. For example,

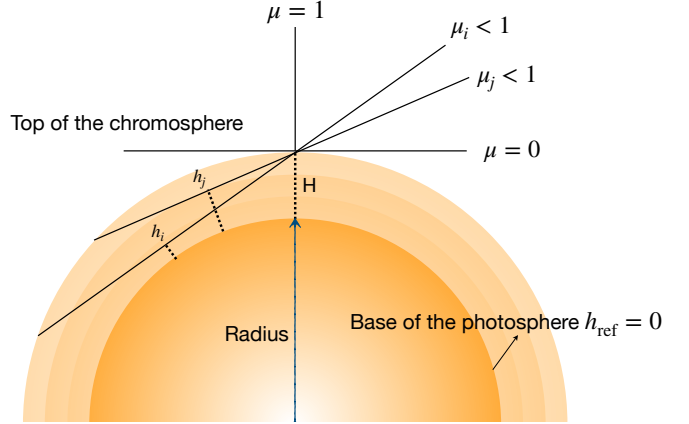
the contrast of dark gap is apparent by comparing the profile intensities at, e.g.,  $\Delta\lambda = \pm 0.5 \text{ \AA}$ . Generally, the H $\beta$  wing intensities of the dark gap profile at 0.6 Mm are reduced over the wavelength spans  $(-0.9, -0.3) \text{ \AA}$  and  $(0.4, 1.1) \text{ \AA}$  compared to the MOLE profile. H $\beta$  reversed core in the dark gap is very close to the MOLE profile.

The left panel of Figure 4 shows the Ca II blue wing image at the wavelength position  $\Delta\lambda = -0.945 \text{ \AA}$  from the line center taken on 2018 June 22 at 08:34:27 UT at the western limb. The middle panel shows the monochromatic intensities extracted along the red dash in the left panel. The image and the intensity extractions at all wavelength positions across Ca II line scan lack any trace of dark gap. Here the observable photospheric limb is also defined by the position of inflection point of intensity gradient along the red dash in the Ca II far wing image at  $\Delta\lambda = -1.75 \text{ \AA}$  (not shown). The position shifted about 0.35 Mm defines the height  $h$  used at  $x$  axes in the middle and right panels. Here we omit the adjective ‘reference’ and the subscript  $_{\text{ref}}$  to distinguish  $h$  from its H $\beta$  and RH counterpart  $h_{\text{ref}}$ . This is because the end wavelength settings of the Ca II scans at  $\Delta\lambda = -1.75 \text{ \AA}$  do not reach yet a true photospheric continuum thus introducing an unknown but likely small off-set between the  $h$  and  $h_{\text{ref}}$  scales. Remarkably, the middle panel of Figure 4 clearly shows a small intensity enhancement at  $\Delta\lambda = -0.945 \text{ \AA}$  over the height span from 0.1 to 0.25 Mm. Such enhanced off-limb intensities are observed within the wavelength spans  $(-0.945, -0.6) \text{ \AA}$  and  $(0.6, 0.945) \text{ \AA}$  of Ca II profile.

#### 4. RH CODE AND VIEWING GEOMETRY

To interpret the observational characteristics of the off-limb H $\beta$  and Ca II line emissions we generated synthetic line profiles with the radiative transfer code RH by Uitenbroek (2001). RH can calculate spectral line profiles for a model atmosphere by solving the equations of statistical equilibrium and radiative transfer under the non-LTE conditions. We utilized the one-dimension spherical version of RH code. Spherical geometry takes into account the tangential variation of physical parameters along the line of sight (LoS), including optical depth which is the main quantity for radiative transfer calculations. This makes spherical RH the most appropriate choice for calculations of off-limb emissions.

To synthesize the line profiles, we chose the SE model of a bright area of the network FAL-F (Fontenla et al. 1993) extending about 2 Mm from the base of the photosphere to the top of the chromosphere. This choice was motivated by an assumption that the formation of



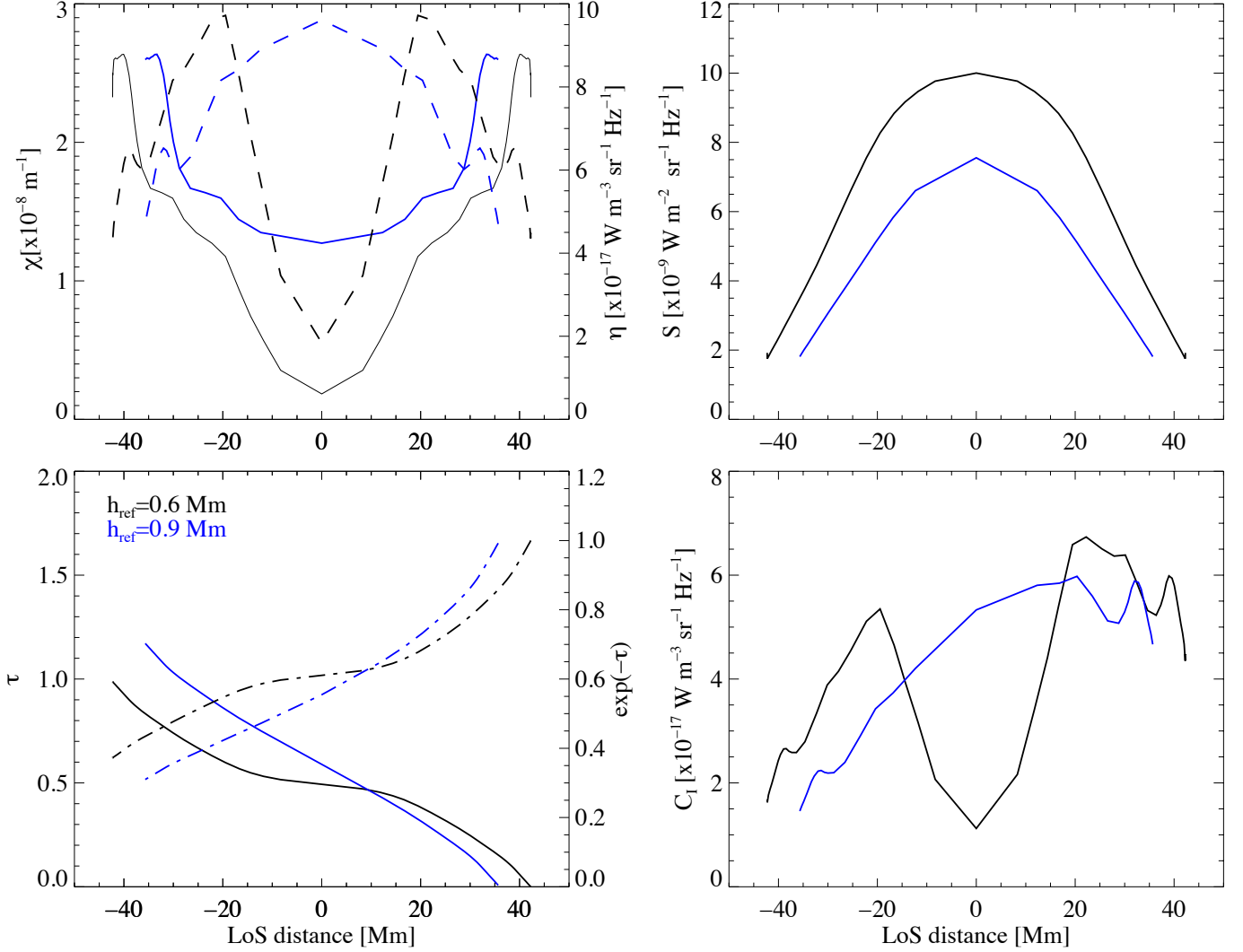
**Figure 5.** Sketch of off-limb geometry showing the line-of-sight rays passing at different heights  $h_i$  and  $h_j$  above the base of the photosphere. The RH code computes emergent intensities at the top of the model atmosphere. As a result  $\mu = 0$  corresponds to the emergent intensity at the height  $H = 2 \text{ Mm}$  above the base of the photosphere at  $h_{\text{ref}} = 0$ .

the H $\beta$  and Ca II lines in the dark gap is affected by the remnants of decaying AR NOAA 12714 seen at the limb in the context Ca II K and H $\alpha$  images (Figure 2) taken by the ChroTel.

We used the models of the hydrogen and singly ionized calcium atom with the five bound levels plus continuum with the complete frequency redistribution for the former (apart from the Ly $\alpha$  and Ly $\beta$  transitions which were calculated in partial frequency redistribution (PRD)) and the PRD with the cross-redistribution for Raman scattering for the latter.

The RH computes emergent intensities at the top of the model atmosphere at 81 pre-defined direction cosines  $\mu_i$ , indexed as  $i = 1 \dots 81$ , from the disk center at  $\mu_{81} = 1$  to the top of the chromosphere at  $\mu_1 \sim 0$  assumed at the height  $H = 2 \text{ Mm}$  above the base of the photosphere. Figure 5 shows a sketch of viewing geometry of different LoS rays passing closer to  $(\mu_i, h_i)$  or further from  $(\mu_j, h_j)$  the base of the photosphere corresponding to the reference height  $h_{\text{ref}} = 0$ . Note that  $\mu_i > \mu_j$  and  $h_i < h_j$  in this sketch. Therefore, in our RH calculations  $\mu_1 \sim 0$  and  $\mu_{67} \sim 0.078$  correspond to the tangential rays touching the top of the chromosphere and the base of the photosphere, respectively. Thus the rays along  $\mu_i$  with  $0 < i < 67$  represent emissions emerging from different heights between  $h_{\text{ref}} \sim 0$  to  $\sim 2 \text{ Mm}$  (Figure 5) in the direction of LoS. The conversion formula between the pre-defined direction cosines  $\mu_i$  and the corresponding reference heights  $h_{\text{ref},i}$  reads

$$h_{\text{ref},i} = (\mathcal{R}_{\odot}^{\text{N}} + H) \sqrt{1 - \mu_i^2} - \mathcal{R}_{\odot}^{\text{N}}, \quad (1)$$



**Figure 6.** Formation characteristics of the  $H\beta$  blue wing intensities at  $\Delta\lambda = -0.44 \text{ \AA}$  shown along the line of sight in the dark gap at the reference height  $h_{\text{ref}} \sim 0.6 \text{ Mm}$  (black) and at the maximum off-limb emissivity at  $0.9 \text{ Mm}$  (blue). Top left: Opacity  $\chi$  (left y axis) and emissivity  $\eta$  (right y axis) as the solid and dashed lines, respectively. Top right: The source function  $S$ . Bottom left: The optical depth  $\tau$  (left y axis) and the exponential  $\exp(-\tau)$  (right y axis) shown as the solid and dash-dotted lines, respectively. Bottom right: The intensity contribution function  $C_I$ .

where  $\mathcal{R}_{\odot}^{\text{N}}$  is the nominal solar radius.

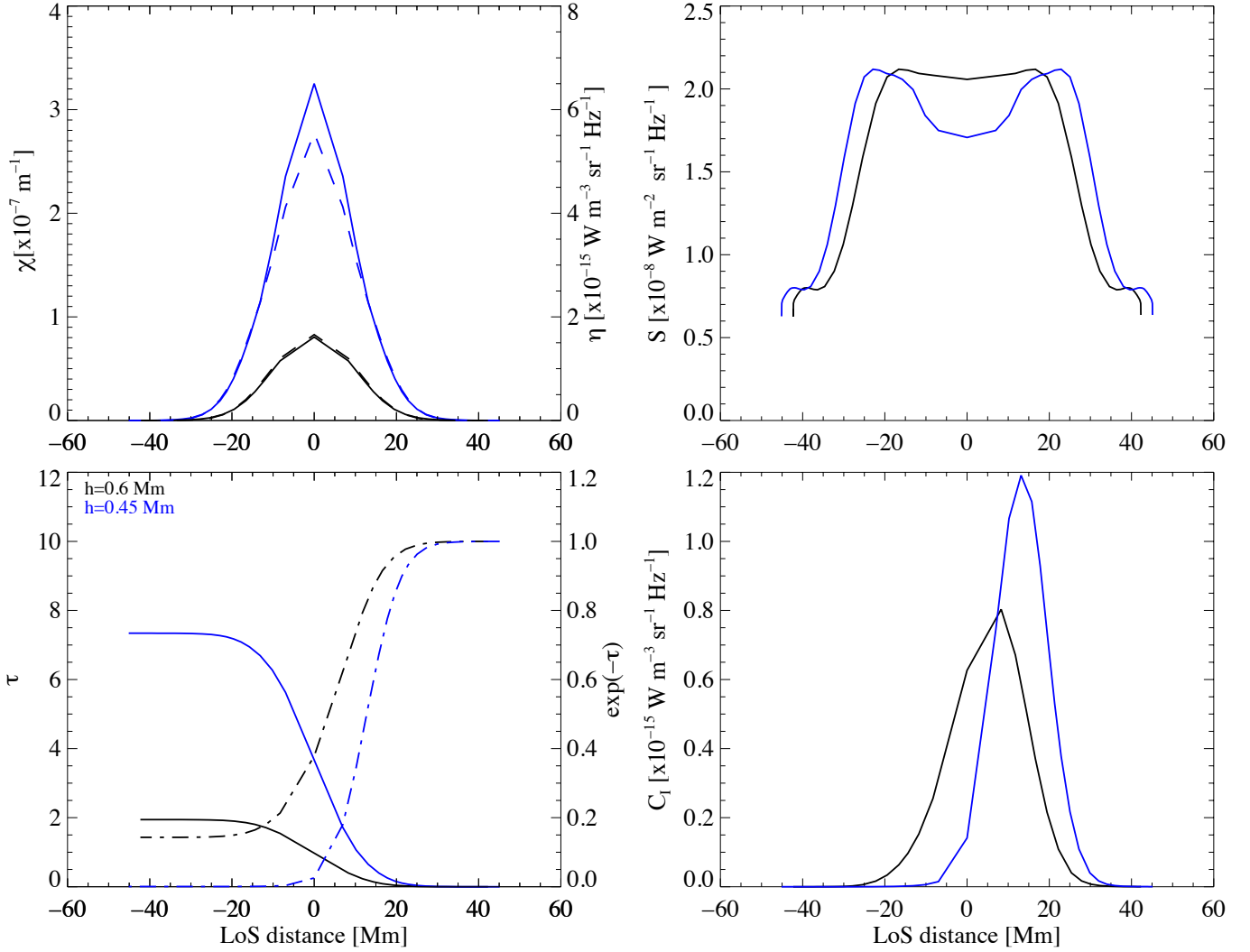
#### 4.1. Synthetic $H\beta$ and $Ca II 8542 \text{ \AA}$ line profiles

The synthetic emergent monochromatic intensities of the  $H\beta$  line along off-limb LoS rays as a function of the reference height  $h_{\text{ref}}$  (Section 3.1) are presented in the bottom middle and right panels of Figure 3 for the three spectral positions. Middle panels show intensities for FAL-F atmosphere with standard microturbulence velocity input. While intensity dip (i.e., the dark gap) is detected at the height of  $0.6 \text{ Mm}$  at the blue wing spectral position of  $\Delta\lambda = -0.5 \text{ \AA}$  there are no intensity variations in the line core (bottom middle panel of Figure 3). The top middle panel of Figure 3 shows the synthetic  $H\beta$  dark gap and MOLE profiles at  $h_{\text{ref}} \sim 0.6 \text{ Mm}$  and

$0.9 \text{ Mm}$ , respectively. It demonstrates that the wing intensities of the MOLE profile are only slightly enhanced over the wavelength spans  $|\Delta\lambda| \in (0.35, 0.55) \text{ \AA}$  compared to the  $H\beta$  line wing intensities at the height of  $0.6 \text{ Mm}$ . It produces a synthetic contrast observable as the dark gap.

We have also synthesized line profiles for FAL-F model with increased microturbulence in the chromosphere (right panels of Figure 3). In FAL-F, at height range covering  $\sim 0.8 - 1.4 \text{ Mm}$   $v_{\text{mic}}$  varies between  $\sim 1$  and  $5 \text{ km s}^{-1}$ . We took  $v_{\text{mic}}(h_{\text{ref}} = 0.8 - 1.5 \text{ Mm}) \sim 4 - 13 \text{ km s}^{-1}$  in the FAL-F model. Here we use quite different viewing angle (off-limb) than in SE models like FAL (on-disk) and we assume that the projected LoS velocities have a larger scatter. Resulted line profile and





**Figure 7.** Formation characteristics of the Ca II 8542 Å blue wing intensities at  $\Delta\lambda = -0.6$  Å shown along the line of sight at the heights  $h \sim 0.45$  Mm (blue) and 0.6 Mm (black). Panel descriptions are the same as in Figure 6.

intensity as a function of height is presented in the right panels of Figure 3. The increased microturbulence produces broader line profiles and higher contrast between the dark gap and MOLE line wing intensities. Furthermore, gap is formed over a wider wavelength range extending toward the outer wings at  $|\Delta\lambda| \in (0.4, 0.85)$  Å (top right panel of Figure 3).

In contrast to  $H\beta$ , the synthetic monochromatic emergent intensities in the Ca II line wings (right panel of Figure 4) along off-limb LoS rays do not show the dark gap but the intensity enhancements at  $h \sim 0.6$  Mm within the wavelength spans of  $(-0.3, -0.6)$  Å and  $(0.3, 0.6)$  Å. We note that the results presented in middle and right panels of Figure 3 and also in the right panel of Figure 4 are convolved with the instrumental characteristics of the CHROMIS and CRISP instruments, respectively.

Finally, the results (synthetic profiles, appearance of the dark gap) obtained through RH calculations with the FAL-F model atmosphere are very similar to those by the FAL-C model (an average region of the quiet Sun). However, due to the better match between absolute observed and synthetic intensities (compare the left and right panels in Figure 3) we give priority to the FAL-F model in this work. Our selection is also justified with context images of the larger FoV confirming that observed limb contains chromospheric bright network, which makes FAL-F more appropriate model for the observed data (Figure 2).

#### 4.2. Understanding the dark gap formation

To understand the off-limb  $H\beta$  and Ca II emissions, we examine their intensity contribution functions  $C_I$  at selected gap-pertinent wavelengths as a function of distance along off-limb LoS rays. Emergent intensity  $I_\nu$  can

be expressed in terms of contribution function (Carlsson & Stein 1994),

$$I_\nu = \int_{\text{LoS}} C_I dl = \int_{\text{LoS}} S_\nu \chi_\nu \exp(-\tau_\nu) dl, \quad (2)$$

where  $S_\nu$  is the source function at the frequency  $\nu$ ,  $\chi_\nu$  is the opacity,  $\tau_\nu$  is the optical depth, and  $l$  is the geometrical distance along LoS. Its zero reference point corresponds to the cross point of viewing LoS ray with the normal to both the photospheric surface and the ray (Figure 5). The positive  $l$  values increase toward the observer.

Figure 6 shows the intensity contribution function  $C_I$  of the FAL-F atmosphere with standard microturbulence input for the H $\beta$  blue wing at  $\Delta\lambda = -0.44 \text{ \AA}$  (bottom right panel) and its components at the dark gap (black curves) and at the point of MOLE (blue curves). To facilitate reading, the panel references omit Figure 6 in this paragraph. For the ray passing through the dark gap the line wings have the lowest opacity  $\chi$  and emissivity  $\eta$  near the limb at  $l = 0 \text{ Mm}$  (black solid and black dashed curves, respectively, in top left panel). The optical depth unity is reached at the farthest point of the dark gap atmosphere at  $l \sim -40 \text{ Mm}$  (black curve in bottom left panel). However, due to the low emissivity  $\eta$  of the dark gap atmosphere (black dashed in top left panel) there is a very little contribution to the emergent intensity over the LoS span  $(-10, 10) \text{ Mm}$  (black curve in bottom right panel). The ray passing through the point of MOLE at  $0.9 \text{ Mm}$  is characterized with a slightly higher optical depth  $\tau$  of about 1.2 (blue curve in bottom left panel). However, a high emissivity  $\eta$  at this point over the LoS span  $(-10, 10) \text{ Mm}$  (blue dashed in top left panel) yields a higher emergent intensity than in the dark gap (blue curve in bottom right panel).

Figure 7 shows the intensity contribution function  $C_I$  for the Ca II blue wing at  $\Delta\lambda = -0.6 \text{ \AA}$  (bottom right panel) and its components at the point of MOLE at  $0.6 \text{ Mm}$  (black curves, see also right panel of Figure 4), coinciding with the height of H $\beta$  dark gap, and at the height of  $0.45 \text{ Mm}$  (blue curves) selected for comparison.  $C_I$  components indicate that ray passing through the atmosphere at  $\sim 0.6 \text{ Mm}$  experiences low opacity  $\chi$ , low emissivity  $\eta$ , and optical depth  $\tau$  (top left and bottom left panels of Figure 7) resulting in optically thin emission. At  $\sim 0.45 \text{ Mm}$  the rays originate in an optically thicker environment at  $\tau \sim 7$  attenuating the emissivity through the factor  $\exp(-\tau)$ . As a result, the off-limb emission at Ca II line wing, emerging at  $\sim 0.6 \text{ Mm}$ , has higher intensity than at  $\sim 0.45 \text{ Mm}$ .

#### 4.3. Understanding dark gap visibility didactically

**Table 1.** Parameters of prominent chromospheric lines.

Atom/Ion	$\lambda$ ( $\text{\AA}$ )	$E_{\text{low}}$ (eV)	$E_{\text{low}}/k_B T_e^a$
He I D3	5876	21.0	34.8
He I	10830	19.8	32.8
H $\alpha$	6563	10.2	16.9
H $\beta$	4861	10.2	16.9
O I	7772	9.1	15.1
Ca II	8542	1.7	2.8
Ca II K	3934	0.0	0.0
Ca II H	3968	0.0	0.0

<sup>a</sup>computed for a typical chromospheric electron temperature  $T_e \sim 7000 \text{ K}$ .

In the previous Section 4.2 we attempted to render a rigorous explanation of dark gap visibility in the context of the TM region. Here we offer a more straightforward account for why the dark gap is visible in H $\beta$  and other chromospheric lines, listed in Section 1, but not in Ca II.

The line opacity is proportional to the fraction of atoms (or ions) excited to the  $n$ th level which scales with the Boltzmann factor as  $\text{const} \times g_{\text{low}} e^{-E_{\text{low}}/k_B T_e}$ , where  $g_{\text{low}}$  and  $E_{\text{low}}$  is the statistical weight and energy of lower level of transition, respectively,  $k_B$  is the Boltzmann constant, and  $T_e$  is the electron temperature (Gray 2008). Table 1 shows the lower level energies and the exponents of the Boltzmann factor for  $T_e \sim 7000 \text{ K}$  for prominent chromospheric spectral lines. The lines with  $E_{\text{low}} \gg 1 \text{ eV}$  have high Boltzmann factor exponent suggesting they should have low opacities in the chromosphere. This explains why the dark gap is well visible in the He I, Balmer, and O I lines but hardly or not at all in the Ca II line.

However, the Ca II H and K lines throw uncertainty on the proposed scenario which suggests that a presence or absence of dark gap is controlled by the  $E_{\text{low}}$  of transition. The model calculations of Ca II H by Judge & Carlsson (2010, Figure 5) never remove the off-limb dip entirely which should not appear at all like in our observations and calculations of Ca II 8542  $\text{\AA}$ .

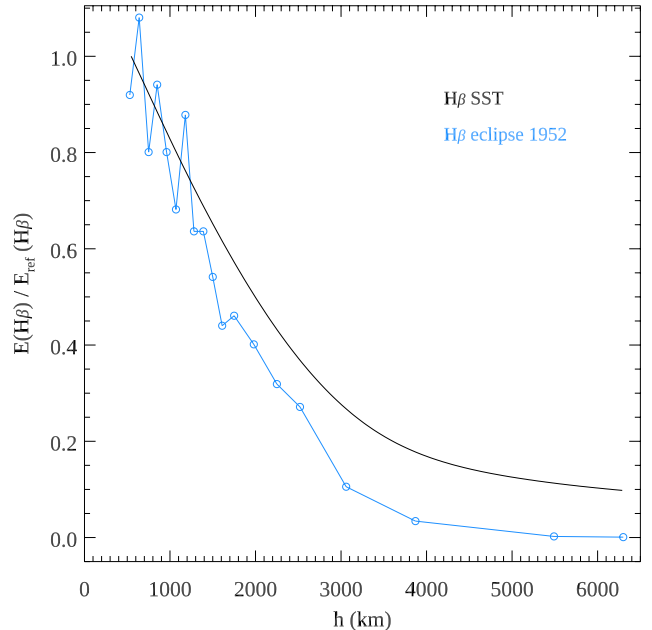
## 5. DISCUSSION

The wing detection of the dark gap and its absence in the H $\beta$  core is particularly significant in the context of previous gap detection in H $\alpha$ , He I D3, and O I 7772  $\text{\AA}$  reviewed in Section 1. The gap detection in H $\alpha$  pertained to wide-band observations blending the line center and wing intensities. High inherent opaqueness of the chromosphere in the H $\alpha$  center enhanced further by the spicules and the chromospheric canopy, prevents observing the dark gap in the H $\alpha$  center. We consider the past H $\alpha$  detection in fact for wing detection in the

regime of low  $H\alpha$  optical thickness outside the thick opacity wall due to the spicules and the canopy. On the other hand, the recent narrow-band gap detection by the SST/CRISP in the He I D3 and O I 7772 Å centers give evidences about low inherent optical thickness of the chromosphere (Pazira et al. 2017,  $\tau$  in Figure 7), the spicules and the canopy in these lines. We note that in Pazira et al. (2017) there is around 170 km difference between the location of the dark gap in observed and synthetic O I 7772 Å line core intensities (Pazira et al. 2017, Figure 6). For  $H\beta$  analyzed in this work, both the observed and synthetic gaps, computed by the FAL-F and FAL-C models, are located at  $\sim 0.6$  Mm suggesting that  $H\beta$  line wing images could be better tracer of TM layer.

There are noticeable differences between properties of the dark gap in observations and the RH radiative transfer simulations. In particular, (i) the observed contrast of the dark gap with respect to maximum off-limb emission is larger in observations than in the RH simulations (bottom panels in Figure 3); (ii) the observed  $H\beta$  profiles are broader and asymmetric compared to the synthetic profiles (top panels in Figure 3); (iii) dark gap is seen along a wider spectral range in the observation covering around  $|\Delta\lambda| \in (0.4 - 1)$  Å, at the blue and red wings, whereas with standard FAL-F microturbulence velocities, gap is only detected at  $|\Delta\lambda| \in (0.35, 0.55)$  Å. We explain these differences as due to absence of a realistic model of spicules and the chromospheric canopy in the RH simulations. Spicule emission contributes to the observed emergent intensities in the layers above the dark gap thus enhancing the observed contrast. Spicule hydrogen profiles of the Balmer series are broad with enhanced and asymmetric wings (Beckers 1972; Shoji et al. 2010). It likely makes the observed  $H\beta$  profiles broad and asymmetric as captured in our observations. To investigate the effect of extra broadening introduced by chromospheric dynamics such as spicules, flows, jets, MHD waves, we performed a simple test by using increased microturbulence in FAL-F model at the heights of 0.8–1.5 Mm above the photosphere. Resulted profiles showing broad line width and presence of the dark gap at the outer wing positions at  $|\Delta\lambda| \in (0.4, 0.85)$  Å, are in a good agreement with the observations (top left and right panels of Figure 3).

The dark gap is absent in Ca II, both in observations and simulations (Figure 4). As discussed in Cauzzi et al. (2008), an opacity gap in the Ca II line wings is less prominent due to the much lower excitation energy of 1.7 eV of the D term of the Ca II infrared triplet compared to the excitation energy of hydrogen upper levels 10.2 eV (Table 1). Furthermore, the low optical



**Figure 8.** Relative  $H\beta$  height gradients,  $E/E_{\text{ref}}$ . The wavelength- and area-integrated intensity  $E$  of the  $H\beta$  line as a function of the height above the photospheric limb  $h$  derived from the SST/CHROMIS spectral imaging at the limb on 2018 June 22 (black) and from the flash spectra (blue) obtained at the 1952 eclipse in Khartoum (Athay et al. 1954, Table 2). The SST intensities  $E$  are normalized with respect to ad-hoc reference intensity  $E_{\text{ref}}$  at  $h = 530$  km. The eclipse intensities  $E$  are normalized with respect to the ad-hoc reference value  $E_{\text{ref}}$  taken as an average of the intensities at the heights 530 km and 640 km.

depth of the Ca II line wing emission produces higher off-limb synthetic emergent intensity at  $\sim 0.6$  Mm than at  $\sim 0.45$  Mm from the photospheric limb (Figure 4 and 7).

In the past, eclipse flash spectra provided a sound basis for determining physical conditions in the chromosphere (Athay et al. 1954; Judge et al. 2019). Out of the wealth of continuum and line spectral data presented therein we concentrate further just on the  $H\beta$  data (Athay et al. 1954, Table 2). The  $H\beta$  flash spectra sampled the quiet-Sun chromosphere over the heights from 530 km up to 6300 km above the photospheric limb yielding twenty samples with the regular cadence of 0.4 s and step size of 110 km in the lower chromosphere but increasing higher up. Notice the blue circles in Figure 8 comparing the wavelength- and area-integrated  $H\beta$  intensity  $E$  as a function of the height  $h$  above the photospheric limb derived from the SST/CHROMIS data (black) and the 1952 eclipse flash spectra shown also in Athay (1976, page 177, Fig. V-7.). Both gradient curves compare well in the low chromosphere up to  $h \sim 2000$  km. Higher up they bear on spicules as

broadly discussed in Athay (1976). The SST curve indicates relatively brighter spicules than those captured by the eclipse flash spectrum. This is in full agreement with the results by Judge & Carlsson (2010, Figure 5) showing brighter spicules in the Ca II H images acquired in the polar coronal hole than those captured in the flash spectrum. It was shown in Athay (1976, Chapter II) that when even 0.1 to 1% of the disk area is covered with spicule-like features the effects at the limb are dramatic. It is entirely possible, and probable as well, that nearly all of the emission at the limb above heights of 1500 km arises in spicules covering less than 1% of the solar surface (Athay 1976, page 305). These same spicules would have quite negligible effect on much of the emission observed near the disk center (Judge et al. 2020). Assuming that the limb is completely covered by spicules at  $h \sim 3000$  km and that at  $h \sim 5000$  km the mean fraction of the limb covered by spicules is approximately 10%, Athay (1976, pages 178–179) suggested that most of the decrease in H $\beta$  brightness above 3000 km is due to the decreasing of surface area of spicules. The plausibility of this suggestion is demonstrated in Fig. VII–9 by Athay (1976, page 305) showing the relative decrease of spicule numbers and the H $\beta$  emission. Thus, the spicule number distribution falls off more slowly with height than does H $\beta$  emission (Athay 1976, page 305). It follows that if the spicules are effectively thin and have outwardly decreasing material density they can account for the observed H $\beta$  line emission above a height of about 2500 km (Athay 1976, pages 305–306, Fig. VII–10).

Judge et al. (2020) examined possible candidates of the differences in central reversal (center-to-peak ratio) between observed and synthetic chromospheric lines such as Ly $\alpha$ , Mg II h and k, Ca II H and K. They analyzed disk profiles and concluded that micro and macro turbulence are not responsible for the observed discrepancies. They also admitted that the area coverage of spicules is too small to contribute significantly to the spatially averaged profiles (page 4 therein, left column). However, as it has been mentioned above the effects of spicules at the limb are dramatic (Athay 1976, page 305) as more spicules are expected to be aligned along the LoS. Our motivation to invoke enhanced microturbulence was sparked by the results presented in Tei et al. (2020) proving a profound effect of microturbulence on the Mg II h and k profiles of spicules computed by multi-slab non-LTE modeling. A question may arise whether macro-turbulence may account for the dark gap as well. An effect of macro-turbulence on a line profile is formally represented by a convolution affecting inevitably the whole line profile including its core. However, as we show in Figures 1 and 3 the dark gap pertains only line

wings and not the core. This excludes macro-turbulence from any considerations and keeps micro-turbulence as a viable representation of multitude of spicules at the limb in radiative transfer calculations by the spherical RH code.

## 6. CONCLUSIONS

We have analyzed high-resolution off-limb imaging spectroscopy in the H $\beta$  and Ca II 8542 Å lines and compared them with radiative transfer computations. The H $\beta$  line wing images and intensity profiles of off-limb wing emissions show the dark gap at the height about 0.265 Mm above the apparent photospheric limb (Figure 1) corresponding to the height 0.6 Mm above the base of the photosphere (bottom left panel of Figure 3). The gap disappears in the line core and far wing images at  $|\Delta\lambda| \gtrsim 1$  Å. Due to a spherical symmetry of the solar atmosphere, off-limb LOS chromospheric rays are passing through a very long ( $\sim 100$  Mm) geometrical path length covering very dynamic and non-homogeneous chromospheric layers. Therefore, to understand the formation of the dark gap radiative transfer calculations need to be performed for off-limb emissions in spherical geometry.

The synthetic H $\beta$  profiles, computed by the RH code and the FAL-F model along off-limb line-of-sight rays, confirm the existence of the dark gap at the height of 0.6 Mm, which is close to the temperature minimum region of the FAL-F atmosphere at about 0.525 Mm. The temperature of this region  $\sim 4500$  K is too low to populate upper hydrogen levels resulting in the opacity and emissivity gap (Cauzzi et al. 2008; Leenaarts et al. 2012). The off-limb line-of-sight ray, passing at the height of  $\sim 0.6$  Mm, samples a large segment of the TM region with meager population of relevant H $\beta$  levels (Figure 5). The components of the intensity contribution function show that a strong opacity and emissivity gap in this layer makes the local plasma and the H $\beta$  line wing emission at e.g.,  $|\Delta\lambda| \sim 0.4 - 0.5$  Å optically thin. On the contrary, the line-of-sight ray at  $\sim 0.9$  Mm already samples layers with high H $\beta$  wing emissivity above the temperature minimum region thus producing an observable intensity contrast with the dark gap (top panels of Figure 1). We interpret the slight difference between the height of the TM at 0.525 Mm in the FAL-F model and the height of the dark gap at 0.6 Mm as a consequence of location of electron density minimum in FAL-F at 0.6 Mm. It shifts the opacity minimum and the dark gap above the TM layer.

The gap near TM region was also detected in off-limb observations of X8.2 class flare analyzed in Kuridze et al. (2019, 2020) (see Figure 2 in Kuridze et al. 2020). This

indicates that  $H\beta$  off-limb observations can map the TM region under different atmospheric conditions.

The dark gap is absent in the  $H\beta$  line core images (bottom left panel of Figure 3). Its absence is due to a combination of opacity maximum in the line core at all off-limb positions which is boosted by high opaqueness of spicules and chromospheric canopy in the  $H\beta$  core hiding the dark gap beyond a thick opacity wall. The dark gap absence in the  $H\beta$  core is reproduced in the RH radiative transfer calculations (bottom middle and right panels in Figure 3) even without including a model of chromospheric canopy and spicules.

We demonstrate here that the off-limb emission in the  $H\beta$  wings shows high-contrast gap that maps the TM region. Furthermore, our analyses showed that enhanced microturbulence in the chromosphere is required to reproduce the gap in the outer line wing spectral positions. The nature of such an extra microturbulence can be various dynamical phenomena, such as spicules, MHD waves, jets, shocks. The work opens a new window for studying the TM region by other lines of the Balmer series and with more realistic chromospheric model atmosphere which includes various dynamic phenomena relevant for the chromosphere. Trial  $H\alpha$  computations by the RH code and the FAL-C/F models (not shown here) also show the dark gap in the wings. However,  $H\alpha$  has larger optical thickness than  $H\beta$  with narrower line width which makes an effect of spicules on the emergent intensities more important. These factors can make the  $H\beta$  line a better candidate for off-limb mapping of the TM region. The higher Balmer lines (e.g.,  $H\gamma$ ) can likely produce even better contrast between the TM layer and the upper layers.

D.K acknowledge Science and Technology Facilities Council (STFC) grant ST/W000865/1, Leverhulme grant RPG2019-361 to Aberystwyth University and the excellent facilities and support of SuperComputing Wales. The Swedish 1-m Solar Telescope is operated on the island of La Palma by the Institute for Solar Physics of Stockholm University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. J.K. acknowledges the project VEGA 2/0048/20. P.H. was supported by grant of the Czech Funding Agency No. 19-09489S and by the program 'Excellence Initiative - Research University' No. BPIDUB.4610.96.2021.KG of the University of Wrocław. R.O. acknowledges support from R+D+i project PID2020-112791GB-I00, financed by MCIN/AEI/10.13039/501100011033. ChroTel is operated by the Leibniz-Institute for Solar Physics in Freiburg, Germany, at the Spanish Observatorio del Teide, Tenerife, Canary Islands. The ChroTel filtergraph has been developed by the Leibniz-Institute for Solar Physics in cooperation with the High Altitude Observatory in Boulder, CO, USA. We would like to thank the anonymous referee for comments and suggestions that helped improve this paper.

*Software:* RH code (Uitenbroek 2001)

*Facility:* SST(CRISP, CHROMIS), Chromospheric Telescope (ChroTel)

## REFERENCES

- Alissandrakis, C. E., & Macris, C. J. 1971, *SoPh*, 20, 47, doi: [10.1007/BF00146093](https://doi.org/10.1007/BF00146093)
- Athay, R. G. 1976, *The solar chromosphere and corona: Quiet sun*, Vol. 53 (D. Reidel Publishing Company), doi: [10.1007/978-94-010-1715-2](https://doi.org/10.1007/978-94-010-1715-2)
- Athay, R. G., Billings, D. E., Evans, J. W., & Roberts, W. O. 1954, *ApJ*, 120, 94, doi: [10.1086/145885](https://doi.org/10.1086/145885)
- Avrett, E. H. 1985, in *Chromospheric Diagnostics and Modelling*, ed. B. W. Lites, 67–127
- Ayres, T. R. 1981, *ApJ*, 244, 1064, doi: [10.1086/158776](https://doi.org/10.1086/158776)
- . 2002, *ApJ*, 575, 1104, doi: [10.1086/341428](https://doi.org/10.1086/341428)
- Ayres, T. R. 2003, in *Astronomical Society of the Pacific Conference Series*, Vol. 286, *Current Theoretical Models and Future High Resolution Solar Observations: Preparing for ATST*, ed. A. A. Pevtsov & H. Uitenbroek, 431
- . 2010, *Highlights of Astronomy*, 15, 547, doi: [10.1017/S1743921310010665](https://doi.org/10.1017/S1743921310010665)
- Ayres, T. R., & Linsky, J. L. 1976, *ApJ*, 205, 874, doi: [10.1086/154344](https://doi.org/10.1086/154344)
- Beckers, J. M. 1972, *ARA&A*, 10, 73, doi: [10.1146/annurev.aa.10.090172.000445](https://doi.org/10.1146/annurev.aa.10.090172.000445)
- Bethge, C., Peter, H., Kentischer, T. J., et al. 2011, *A&A*, 534, A105, doi: [10.1051/0004-6361/201117456](https://doi.org/10.1051/0004-6361/201117456)
- Bjørgen, J. P., Leenaarts, J., Rempel, M., et al. 2019, *A&A*, 631, A33, doi: [10.1051/0004-6361/201834919](https://doi.org/10.1051/0004-6361/201834919)
- Carlsson, M. 2007, in *Astronomical Society of the Pacific Conference Series*, Vol. 368, *The Physics of Chromospheric Plasmas*, ed. P. Heinzel, I. Dorotović, & R. J. Rutten, 49. <https://arxiv.org/abs/0704.1509>
- Carlsson, M., & Stein, R. F. 1994, in *Chromospheric Dynamics*, ed. M. Carlsson, 47

- Cauzzi, G., Reardon, K. P., Uitenbroek, H., et al. 2008, *A&A*, 480, 515, doi: [10.1051/0004-6361:20078642](https://doi.org/10.1051/0004-6361:20078642)
- Cox, A. N. 2000, *Allen's astrophysical quantities* (4th ed. Publisher: New York: AIP Press; Springer, 2000)
- David, K.-H. 1961, *ZA*, 53, 37
- Fontenla, J. M., Avrett, E. H., & Loeser, R. 1993, *ApJ*, 406, 319, doi: [10.1086/172443](https://doi.org/10.1086/172443)
- Fontenla, J. M., Balasubramaniam, K. S., & Harder, J. 2007, *ApJ*, 667, 1243, doi: [10.1086/520319](https://doi.org/10.1086/520319)
- Gingerich, O., Noyes, R. W., Kalkofen, W., & Cuny, Y. 1971, *SoPh*, 18, 347, doi: [10.1007/BF00149057](https://doi.org/10.1007/BF00149057)
- Gray, D. F. 2008, *The Observation and Analysis of Stellar Photospheres* (Cambridge University Press)
- Heinzel, P., & Štěpán, J. 2019, in *Astronomical Society of the Pacific Conference Series*, Vol. 519, *Radiative Signatures from the Cosmos*, ed. K. Werner, C. Stehle, T. Rauch, & T. Lanz, 59
- Judge, P., Tomczyk, S., Hannigan, J., & Sewell, S. 2019, *ApJ*, 877, 10, doi: [10.3847/1538-4357/ab0e04](https://doi.org/10.3847/1538-4357/ab0e04)
- Judge, P. G., & Carlsson, M. 2010, *ApJ*, 719, 469, doi: [10.1088/0004-637X/719/1/469](https://doi.org/10.1088/0004-637X/719/1/469)
- Judge, P. G., Kleint, L., Leenaarts, J., Sukhorukov, A. V., & Vial, J.-C. 2020, *ApJ*, 901, 32, doi: [10.3847/1538-4357/abadf4](https://doi.org/10.3847/1538-4357/abadf4)
- Kentischer, T. J., Bethge, C., Elmore, D. F., et al. 2008, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7014, *Ground-based and Airborne Instrumentation for Astronomy II*, ed. I. S. McLean & M. M. Casali, 701413, doi: [10.1117/12.789044](https://doi.org/10.1117/12.789044)
- Kuridze, D., Henriques, V., Mathioudakis, M., et al. 2017, *ApJ*, 846, 9, doi: [10.3847/1538-4357/aa83b9](https://doi.org/10.3847/1538-4357/aa83b9)
- Kuridze, D., Mathioudakis, M., Heinzel, P., et al. 2020, *ApJ*, 896, 120, doi: [10.3847/1538-4357/ab9603](https://doi.org/10.3847/1538-4357/ab9603)
- Kuridze, D., Socas-Navarro, H., Koza, J., & Oliver, R. 2021, *ApJ*, 908, 168, doi: [10.3847/1538-4357/abd100](https://doi.org/10.3847/1538-4357/abd100)
- Kuridze, D., Mathioudakis, M., Morgan, H., et al. 2019, *ApJ*, 874, 126, doi: [10.3847/1538-4357/ab08e9](https://doi.org/10.3847/1538-4357/ab08e9)
- Leenaarts, J. 2020, *Living Reviews in Solar Physics*, 17, 3, doi: [10.1007/s41116-020-0024-x](https://doi.org/10.1007/s41116-020-0024-x)
- Leenaarts, J., Carlsson, M., & Rouppe van der Voort, L. 2012, *ApJ*, 749, 136, doi: [10.1088/0004-637X/749/2/136](https://doi.org/10.1088/0004-637X/749/2/136)
- Libbrecht, T. 2016, PhD thesis, Stockholm University, Faculty of Science, Department of Astronomy.
- Lites, B. W. 1983, *SoPh*, 85, 193, doi: [10.1007/BF00148648](https://doi.org/10.1007/BF00148648)
- Löfdahl, M. G., Hillberg, T., de la Cruz Rodríguez, J., et al. 2021, *A&A*, 653, A68, doi: [10.1051/0004-6361/202141326](https://doi.org/10.1051/0004-6361/202141326)
- Loughhead, R. E. 1969, *SoPh*, 10, 71, doi: [10.1007/BF00146156](https://doi.org/10.1007/BF00146156)
- Machado, M. E., & Linsky, J. L. 1975, *SoPh*, 42, 395, doi: [10.1007/BF00149921](https://doi.org/10.1007/BF00149921)
- Maltby, P., Avrett, E. H., Carlsson, M., et al. 1986, *ApJ*, 306, 284, doi: [10.1086/164342](https://doi.org/10.1086/164342)
- Mauas, P. J. D. 2000, *ApJ*, 539, 858, doi: [10.1086/309271](https://doi.org/10.1086/309271)
- Neckel, H. 1999, *SoPh*, 184, 421, doi: [10.1023/A:1017165208013](https://doi.org/10.1023/A:1017165208013)
- Nikolsky, G. M. 1970, *SoPh*, 12, 379, doi: [10.1007/BF00148021](https://doi.org/10.1007/BF00148021)
- Pazira, H., Kiselman, D., & Leenaarts, J. 2017, *A&A*, 604, A49, doi: [10.1051/0004-6361/201630277](https://doi.org/10.1051/0004-6361/201630277)
- Pope, T., & Schoolman, S. A. 1975, *SoPh*, 42, 47, doi: [10.1007/BF00153283](https://doi.org/10.1007/BF00153283)
- Rutten, R. J. 2002, *Journal of Astronomical Data*, 8, 8
- Rutten, R. J., & Uitenbroek, H. 2012, *A&A*, 540, A86, doi: [10.1051/0004-6361/201118525](https://doi.org/10.1051/0004-6361/201118525)
- Scharmer, G. B. 2006, *A&A*, 447, 1111, doi: [10.1051/0004-6361:20052981](https://doi.org/10.1051/0004-6361:20052981)
- Scharmer, G. B., Bjelksjo, K., Korhonen, T. K., Lindberg, B., & Petterson, B. 2003a, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4853, *Innovative Telescopes and Instrumentation for Solar Astrophysics*, ed. S. L. Keil & S. V. Avakyan, 341–350, doi: [10.1117/12.460377](https://doi.org/10.1117/12.460377)
- Scharmer, G. B., Dettori, P. M., Lofdahl, M. G., & Shand, M. 2003b, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4853, *Innovative Telescopes and Instrumentation for Solar Astrophysics*, ed. S. L. Keil & S. V. Avakyan, 370–380, doi: [10.1117/12.460387](https://doi.org/10.1117/12.460387)
- Scharmer, G. B., Narayan, G., Hillberg, T., et al. 2008, *ApJL*, 689, L69, doi: [10.1086/595744](https://doi.org/10.1086/595744)
- Shine, R. A., Milkey, R. W., & Mihalas, D. 1975, *ApJ*, 199, 724, doi: [10.1086/153744](https://doi.org/10.1086/153744)
- Shoji, M., Nishikawa, T., Kitai, R., & Ueno, S. 2010, *PASJ*, 62, 927, doi: [10.1093/pasj/62.4.927](https://doi.org/10.1093/pasj/62.4.927)
- Solanki, S. K., Livingston, W., & Ayres, T. 1994, *Science*, 263, 64, doi: [10.1126/science.263.5143.64](https://doi.org/10.1126/science.263.5143.64)
- Tei, A., Gunár, S., Heinzel, P., et al. 2020, *ApJ*, 888, 42, doi: [10.3847/1538-4357/ab5db1](https://doi.org/10.3847/1538-4357/ab5db1)
- Uitenbroek, H. 2001, *ApJ*, 557, 389, doi: [10.1086/321659](https://doi.org/10.1086/321659)
- Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, *ApJS*, 45, 635, doi: [10.1086/190731](https://doi.org/10.1086/190731)
- Wedemeyer, S., Freytag, B., Steffen, M., Ludwig, H. G., & Holweger, H. 2004, *A&A*, 414, 1121, doi: [10.1051/0004-6361:20031682](https://doi.org/10.1051/0004-6361:20031682)
- White, O. R. 1963, *ApJ*, 138, 1316, doi: [10.1086/147733](https://doi.org/10.1086/147733)
- Wiedemann, G., Ayres, T. R., Jennings, D. E., & Saar, S. H. 1994, *ApJ*, 423, 806, doi: [10.1086/173859](https://doi.org/10.1086/173859)