The Flash Spectrum Analysis during the 2013 Total Solar Eclipse (Postprint)

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Date: 2025-09-28T12:32:54+00:00

Abstract

During the total solar eclipse of November 3, 2013, a fiber optic spectrometer captured flash spectra in the wavelength range of 5162–5325 Å, with a field of view located approximately 0.04 R above the east limb, near second contact. This position close to the innermost corona, together with nearby Baily' s beads, enabled the detection of emission lines from the photosphere, low chromosphere, and corona within the same spectral frame. The elevated field of view rendered the coronal line Fe xiv 5303 Å more clearly visible, while the intensity of photospheric and low chromospheric light, attenuated by scattering in Earth' s atmosphere, also influenced the observed spectra. Simultaneously, we selected 18 flash emission lines to measure the ratio of the relative height of flash emission lines to the relative depth of corresponding solar absorption lines. This ratio serves as a diagnostic tool for the source function, thereby minimizing the effects of opacity. Comparison between disk spectra and flash spectra reveals that this ratio increases with greater line formation height, being strongest in chromospheric lines (particularly Fe II), moderate in photospheric low-FIP lines, and weakest in photospheric neutral lines. This trend suggests that the source function rises with formation height, possibly associated with increasing electron temperature or influenced by factors observed in previous studies reporting on flash spectra near active regions.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:085008 (11pp), 2025 August https://doi.org/10.1088/1674-4527/addd7c CSTR: 32081.14.RAA.addd7c

The Flash Spectrum Analysis during the 2013 Total Solar Eclipse

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Received 2025 March 23; revised 2025 May 13; accepted 2025 May 16; published 2025 June 30

Abstract

During the total solar eclipse of 2013 November 3, a fiber-based spectrometer captured the flash spectrum within the wavelength range of 5162–5325 Å, with the field-of-view positioned approximately 0.04 R above the east limb, near the second-contact point. This placement near the innermost corona, together with the nearby Baily’ s beads, enabled the detection of emission lines from the photosphere, lower chromosphere, and corona in the same spectral frame. The higher field-of-view made the coronal line Fe XIV 5303 Å more visible, while the reduced intensity of photospheric and lower chromospheric light, caused by terrestrial scattering, also influenced the observed spectrum. Meanwhile, we selected 18 flash emission lines to measure the ratio of the relative line height of the flash emission line to the relative line depth of the corresponding solar absorption line. This ratio serves as a diagnostic of the source function, minimizing opacity effects. Comparison of disk and flash spectra shows that this ratio increases for spectral lines at greater formation heights, being strongest for chromospheric lines (particularly Fe II), moderate for photospheric low-FIP lines, and weakest for photospheric neutral lines. This trend suggests a rising source function with formation height, potentially linked to increasing electron temperatures or influenced by factors observed in flash spectra near active regions as reported in earlier studies.

Key words: techniques: spectroscopic -eclipses -Sun: chromosphere -Sun: photosphere -Sun: general

1. Introduction

The flash spectrum is visible only briefly during a total solar eclipse, unveiling a large number of emission lines in the visible band from the solar upper atmosphere. The relationship between flash spectra and solar disk spectra has been studied since the initial recognition of the flash spectrum as a distinct observational phenomenon. Early studies noted that, although the two spectra nearly coincide in line positions, their relative intensities differ markedly, except for highly excited or forbidden lines. This contrast reflects a reversal of the solar disk spectrum and indicates variations in atomic excitation and opacity across spectral lines [?]. The continuum of the flash spectrum arises from Baily’ s beads, which are discrete beams of light from the solar limb passing through lunar valleys during the second or third contact.

These beads carry both the remaining photospheric continuum and the emission feature from the extreme photosphere [?], so that the spectrum includes numerous weak emission lines corresponding to those observed in absorption on the solar disk. The second contact is defined as the moment when the last beam of solar disk light, visible as the final Baily’ s bead through a lunar valley aligned with the Moon’ s motion, disappears. This occurs when the bottom of that valley touches and rises just above the solar limb from the observer’ s perspective, marking the beginning of totality. The third contact is defined in the reverse manner, as the first reappearance of disk light through a lunar valley at the end of totality. In practice, capturing the precise instant of the second or third contact is challenging. As a result, flash spectra sampled near Baily’ s beads during the second or third contact often contain their emission, scattered into the detector by Earth’ s atmosphere [?, ?, ?]. The pseudo-continuum intensity, shaped by blended weak emission lines in the flash spectra, enables determinations of the new solar limb [?, ?, ?]. Additionally, the flash spectrum reveals emission from higher layers of the solar atmosphere, which are otherwise not visible in disk observations. For instance, it reveals the transition-region He II 4686 Å line, which is usually undetectable against the quiet solar disk. This He II emission can be observed even as low as 1 Mm above the solar limb, suggesting that transition-region plasma may extend deeper than traditionally expected, lying lower than predicted by classical hydrostatic models such as the Vernazza, Avrett, and Loeser (VAL) model [?].

Active regions further illustrate the differences between the two spectra: while processes such as sunspots may weaken absorption lines in the disk spectrum, they often lead to stronger emission lines in the flash spectrum [?, ?, ?]. These observations confirmed the significant differences between the flash spectrum and the disk spectrum. While many spectral lines are common to both, others are exclusive to one or the other, depending on the formation conditions and observational perspectives. The appearance of the observed spectrum is shaped by the observing perspective, as shown in the left panel of Figure 1. The visible solar surface, defined by the continuum optical depth reaching one at 5000 Å (τ_{5000} = 1), is depicted as a solid black circle. The surrounding gray band represents the atmospheric layers where photons are formed and escape. The observed intensity at any given wavelength is determined by contributions from the entire atmospheric column along the line of sight, visually represented by the violet-shaded column, and the two perspectives traverse different density and height profiles.

To illustrate the difference in sampling opacity-height profiles at a given wavelength between the (1) disk-center and (2) off-limb perspectives, we consider the dominant escape point for photons, where the optical depth at a given wavelength reaches one (marked by the diamond symbols). The opacity-height profile at a fixed wavelength differs between perspectives: along the disk-center perspective, the main escape point lies at a lower height (h) during a total solar eclipse, the off-limb line of sight intersects the rarefied upper layers, positioning the escape point at a higher height. In the corona, the optical depth remains below one, so the traversed atmosphere is optically thin. The opacity–height profile determines which layer we mainly observe at a given wavelength and perspective. When observing at line center and nearby continuum, the resulting brightness contrast between the relevant layers leads to absorption in the disk-center perspective and emission as part of the flash spectrum, superimposed with both continuum and line features from nearby Baily’ s beads, scattered into the sampled region of the spectrum. The right panel of Figure 1 illustrates the significance of Baily’ s beads, presenting a detailed simulation by Xavier Jubier of the irregular lunar profile projected onto the Sun at mid-totality during the 2013 November 3 total solar eclipse, which is the event analyzed in this study. The black region represents the irregular lunar limb profile, while the golden areas indicate Baily’ s beads emerging through potential lunar valleys during the second and third contact. The Baily’ s beads spectrum, which shines through lunar valleys and appears on the flash spectrum, can be referenced in the work of [**?**].

In this study, we present a detailed analysis comparing the flash spectrum with the solar disk spectrum, with a particular focus on the line-center intensities of selected spectral lines, characterized by the relative line height of emission lines and the relative line depth of absorption lines. Our observations were carried out during the total solar eclipse on 2013 November 3, in Bifoun, Gabon, using the prototype Fiber Arrayed Solar Optical Telescope (FASOT; [**?**]). FASOT captures a two-dimensional field-of-view while simultaneously recording the spectrum at each spatial pixel at one instant, enabling a comprehensive spatial-spectral analysis of the solar atmosphere. The structure of this paper is as follows. In Section 2, we describe the setup of the FASOT spectrometer, the observational conditions during the eclipse, and the steps taken for data preprocessing and calibration. In Section 3, we analyze the preprocessed data to extract the line intensities needed for our study. Section 4 introduces the theoretical background necessary to understand the spectral line intensities, including the role of terrestrial scattering effects, discussing the spectrum intensity distribution and comparing emission and absorption line intensities under different viewing conditions. Finally, Section 6 provides the conclusions.

2. Observation and Data Reduction

The flash spectrum analyzed in this study was recorded during the total solar eclipse of 2013 November 3 in Bifoun, Gabon (S0°17 17 , E10°29 24), using the prototype FASOT at the time of the second contact. The second contact occurred at approximately 13:53:04 UT and corresponded to the moment when the Moon fully obscures the photosphere, indicating the beginning of totality. The observation and reduction methods are similar to those employed in the study of the 2013 total solar eclipse described by Zhu B. et al. (2025, in preparation). Therefore, we briefly present them here. FASOT is equipped with a fiber-arrayed integral field unit (IFU), which offers the advantage of simultaneously capturing both spectral and spatial information. The optical fibers in the IFU are arranged in a 5 × 5 configuration to acquire a two-dimensional field-of-view. These fibers are then linearized into a one-dimensional array to fit into the entrance slit of the spectrometer. Each fiber unit covers a solar region of 2 × 2 , corresponding to a spatial resolution of 2 . During the observation around the second contact, we captured the flash spectrum at approximately Lat. 40°N near the east limb, with our field-of-view extending into the inner corona, reaching no more than 0.04 R above the limb. As a reference, a solar spectrum was recorded before the eclipse near the disk center at 12:16:02 UT.

Figure 2 displays the raw flash spectrum data recorded during the second contact (top panel), alongside an absorption spectrum taken near the solar disk center before the eclipse (bottom panel). The solar disk spectrum serves as a reference for wavelength calibration and provides a basis for contrast. In each spectral frame, the Y direction corresponds to the slit orientation, which consists of 25 fibers, and the X direction represents the dispersion direction. To convert the raw spectral images into scientifically usable data, a comprehensive series of data reduction steps is applied. These include dark-field subtraction, flat-field correction, spectral extraction, slit-inclination correction, and wavelength calibration. The dark-field correction compensates for instrumental stray light and background noise by subtracting the average intensity measured in the edge regions of each spectral frame, areas assumed to contain no useful signal. The flat-field correction is performed using calibration data obtained by uniformly illuminating the detector with a white light source. This step corrects for both pixel-to-pixel gain variations and differences in fiber transmission efficiency, ensuring a uniform response across the detector. Additionally, the flat-field data are used to determine the exact positions of the optical fibers on the detector frame. Spectral extraction is achieved by integrating signal over approximately six detector rows for each fiber, resulting in a total of 25 spatially resolved spectra.

A small but consistent inclination, about one pixel across the slit direction, is identified in all spectral frames. This is corrected by adjusting the slope of a well-defined spectral line observed in the disk-center spectrum, thereby realigning the spectra to be perpendicular to the dispersion direction. The final and crucial step is wavelength calibration, which assigns accurate wavelength values to each spectral pixel. This is accomplished by cross-referencing the observed disk-center spectrum with the high-resolution Fourier Transform Spectrometer solar atlas (https://nispdata.nso.edu/pub/atlas/), and the uncertainty associated with this calibration is approximately 0.24 pixels. Upon completion of this reduction pipeline, we obtain 25 one-dimensional, wavelength-calibrated spectra, each corresponding to a distinct spatial pixel in the FASOT field-of-view. These processed spectra form the basis for our subsequent analysis of line-center intensities and atmospheric diagnostics.

The instrument provides a spectral resolution of approximately 0.12 Å per pixel, which is sufficient to resolve the relatively broad spectral features in the solar atmosphere. The observational wavelength band spans from 5162.60 Å to

5325.08 Å, and encompasses spectral lines formed from the photosphere to the low corona. The spectral lines are identified and labeled in Figure 2. This wavelength range includes the magnesium b triplet, as well as neutral and singly ionized metal lines. Several strong chromospheric emission lines have been identified, including Mg I lines at 5173 and 5184 Å, as well as Fe II lines at 5198, 5235, and 5317 Å. The formation heights of Mg I lines (5173, 5184 Å) are well-documented, approximately several hundred kilometers above the continuum formation layer, primarily within the low chromosphere [**?**, **?**]. Theoretical models suggest that most Fe II lines originate in the photosphere and extend into the low-to-mid chromosphere [**?**]. The behavior of these lines in our data closely resembles that of the Mg I lines, suggesting that they may form within a similar chromospheric region. In addition to these stronger lines, we identify two groups of relatively weaker photospheric emission lines. The first group consists of lines from low first ionization potential (FIP) elements, such as Cr II at 5237 Å and Sc II at 5240 Å, which are believed to originate near the top of the photosphere, close to the region of minimum temperature [**?**, **?**]. The second group includes neutral atom lines, such as Fe I and Cr I, which form within the photosphere [**?**, **?**]. The coronal green line, Fe XIV 5303 Å, is also included in our spectral coverage. This forbidden line, originating from the million-degree plasma of the inner corona, is typically visible during the totality phase in slitless spectral sequences. Its presence in our spectra before totality is due to the field-of-view position, which extended into the low corona above the solar limb, thereby enhancing its visibility.

3. Data Analysis

Figure 3 reveals that emission lines exhibit distinct spatial intensity patterns, reconstructed by integrating the intensity across a selected wavelength interval centered at the line core for each spatial pixel. All emission lines are integrated in this manner, except for Fe XIV 5303 Å, where only the peak intensity is shown due to contamination from a nearby Fe I emission line in its left wing. The bottom-right panel illustrates the spatial mapping of individual pixels relative to the pseudo-slit direction. Lines formed in the lower atmosphere, including photospheric and low chromospheric lines, show significant spatial intensity variations, with their intensity concentrated in the lower-right corner of the field-of-view. In contrast, Fe XIV 5303 Å displays a nearly uniform spatial intensity distribution. While Figure 3 presents the overall spatial intensity distribution of emission lines across the field-of-view, Figure 4 provides a direct comparison of the spectra recorded at two representative spatial pixels: No. 4 and No. 25. The flash spectra differ noticeably, with stronger emission features in pixel No. 4, reflecting the spatial variations seen in the relative intensity distribution. In contrast, the relative intensity profiles of the on-disk spectra at both positions are nearly identical, indicating uniformity across the pixels. A discussion of this pattern is provided in Section 5.

Having examined the intensity spatial distribution of flash emission lines across the field-of-view, we now turn to a spatially integrated analysis for comparison with the disk-center spectrum. As shown in Figure 4, the flash spectrum, recorded off-limb, shows a much lower signal-to-noise ratio than the disk spectrum at the same spatial pixel, due to the greatly reduced brightness in the off-limb region. To improve spectral signal-to-noise and line identification, integration over multiple spatial pixels is required. The integration region was selected based on the spatial intensity distribution, using the set of brighter pixels in the lower-right portion of the field-of-view. This yielded a better-quality one-dimensional flash spectrum. This targeted integration not only enhances the signal-to-noise but also suppresses contamination from the K-corona, which dominates the upper-left region. Figure 5 presents the resulting integrated flash spectrum (upper panel) and the corresponding disk-center spectrum (lower panel), which is integrated over the full field-of-view for comparison. It is evident that spatial integration significantly improves the signal-to-noise of the flash spectrum, allowing emission lines to appear more clearly and be more readily analyzed.

To enable a direct comparison between the flash and disk spectra, we combined both into a single figure, as shown in the upper panel of Figure 6. The solid red line represents the integrated one-dimensional flash spectrum, while the blue one corresponds to the on-disk absorption spectrum, which has been integrated over the full field-of-view. For ease of comparison, the disk spectrum has been inverted so that its absorption lines align with the emission lines in the flash spectrum. Both spectra are normalized to their respective continuum levels. This comparison clearly reveals how spectral line intensities change with observing perspectives. To compare their relative line-center intensities, the continuum intensity must be subtracted; in other words, only the depth (for absorption lines) or height (for emission lines) of each spectral line relative to the continuum level should be considered. These spectral line parameters are defined as the relative line depth (d_0) for absorption lines and the relative line height (h_0) for emission lines. In the bottom panel of Figure 6, we present the values of these parameters at the line center for each spectral line. Additionally, the emission-to-absorption ratio ($_0$) is calculated to facilitate a direct comparison between corresponding emission and absorption lines.

To explore the potential dependence of the spectral parameters (d_0 and h_0) on formation height, we selected several "pure" spectral lines. These are defined as lines that are minimally affected by blending with neighboring lines originating from significantly different atmospheric layers. For example, blended lines such as the Mg I and Fe I line near 5164 Å were excluded to ensure reliability in height attribution. The measured values of the spectral line parameters for these carefully chosen lines are summarized in Table 1, and their trends with respect to estimated formation height are plotted in Figure 7.

4. Theoretical Expressions

In this section, we present the theoretical expressions of the previously introduced spectral line parameters: relative line depth (d_0), relative line height (h_0), and their ratio ($_0$). This will help build a basic theoretical understanding of the physical meaning of these parameters. The emergent intensity from the gray circular band in Figure 1 for the disk-center and off-limb lines-of-sight, without considering external contributions, at a given wavelength λ, I_λ^*, is determined by integrating the source function along the line-of-sight optical depth profile. The optical depth represents the cumulative absorption and scattering along the path and is determined by the local opacity profile, which is proportional to the number density of atoms and the extinction cross-section.

In this study, we focus on the line-center intensity, particularly for spectral lines with different opacity profiles, such as Mg I b1 and Fe I. To simplify the analysis, we illustrate the line formation region as an atmosphere with exponentially decreasing density and employ a constant source function, S_λ. The two observational cases are represented by violet unit columns (see Figure 1), each intersecting the atmosphere. This assumption is valid when the opacity differences between lines predominantly influence the emergent intensity, even if the source function varies with depth. Therefore, I_λ^* simplifies to be the product of the source function and the optical thickness along the line-of-sight, I_λ^* = S_λ τλ, *where* τλ is the optical thickness along the line-of-sight. This optical thickness differs between the two cases, as each samples a distinct density profile through the atmosphere. The optical thickness is an integral of opacity along the geometric light path, τλ = {los} αλ *ds* = σλ *{los} n ds, where* αλ means the opacity, σλ *the extinction cross-section which reflects the optical property of an atom and s is the path light traveled. So the optical thickness is proportional to the total number of atoms N along the line-of-sight,* τλ N. The vertical number density profile is described by an exponential decay n(h) = ae^{-bh}, following the analytic form given by [**?**], where a represents the base number density, b is the vertical decay scale, and the variable h denotes the universal height above the base. In the disk-center case, the number of atoms per unit column along the line-of-sight is given by: N_ = _0^∞ n(h) dh = a/b.

For the off-limb perspective, scattered light primarily originating from the low chromosphere and upper photosphere is received from the Earth' s atmosphere. The contributing atoms include those from all atmospheric layers above the limb, as the terrestrial scattering effect causes the local line-of-sight to be shifted throughout the entire formation region above the limb. At each distance above the limb, an atmospheric column is considered to contribute to the off-limb intensity through scattered light. In our coordinate system for Case (2), this distance lies along the vertical y-axis, so y is used as the variable of integration. For an arbitrary point within this column, x is defined as the horizontal coordinate along the line of sight and is related with the variable y as x = √(R_ ^{2} - (R_ + y)^2). The total number of atoms for the off-limb case can be approximated as: N_ (h) = *0^h* {-x(y)}^{x(y)} n(y) dx dy. Here, we assume n(y) =

ae^{-by} for simplicity. To allow a meaningful comparison with the disk-center case (Case 1), we normalize the off-limb case by dividing by h, so that Ñ = *N* (h)/h corresponds to an effective unit column.

Thus, the relationship between the normalized off-limb and disk-center number of atoms can be expressed as, Ñ /*N* = , with the dimensionless parameter = (b/R_)^{1/2}. Given typical values of the parameters, should be much less than 1, indicating that the normalized number of atoms in the off-limb case is significantly smaller than in the disk-center case. This difference arises because the off-limb line-of-sight traverses a more rapidly decaying density profile, while the disk-center line-of-sight accumulates atoms from a denser vertical column. The optical thicknesses relate as, τ = τ .

Scattering in the Earth' s atmosphere significantly impacts the off-limb observations, as it can elevate light from the lower atmosphere into our field-of-view, which is positioned near the innermost corona. To simplify the analysis, we approximate the intensity generated by the normalized unit column in Case (2) as a point source, which subsequently undergoes scattering in the Earth' s atmosphere. The intensity of singly scattered light, denoted as I_λ,sca^*, at a distance r in the far-field, is given by [**?**]: I_λ,sca^ =* I_λ^* (σλ,*sca P)/(4πr^2), where* σλ,sca is the scattering cross-section for a single type of particle in the Earth' s atmosphere, P is the phase function that determines the angular distribution of scattered light, r is the distance from the scattering source to the observation point, and the whole scattering function is denoted as F = σ_λ,sca P/4πr^2.

The appearance of the spectral line is defined within the context of the background light. We present the line-center intensity generated along the line-of-sight column against the corresponding background light for each observational case. In Case (1), which corresponds to the disk-center viewing perspective, the line-of-sight column intensity is given by I_λ = I_c(1 - e^{-τ *}) + I_c e^{-τ* }, with the background continuum being the transmitted photospheric continuum intensity I_c. We adopt τ *as the line-center effective optical thickness in case (1). In Case (2), representing an off-limb line-of-sight observed during a total solar eclipse, the emergent intensity of the normalized unit column, modified by scattering, is given by Iλ =* I_c γ (1 - e^{-τ *}) + I_c γ e^{-τ* }. Here, τ *represents the optical thickness in case (2), modified by the observing perspective effect relative to Case (1). The background continuum in this case is the superposed Baily' s beads spectrum, where the continuum intensity is reduced to a fraction γ of the disk-center photospheric continuum intensity due to lunar obscuration. The resulting expressions for the two cases describe the observed intensities at the line center (Iλ*) and in the neighboring continuum (I_c) as follows:

Case (1): I_λ = I_c (1 - e^{-τ *}) + I_c e^{-τ* }
Case (2): I_λ = I_c γ (1 - e^{-τ *}) + I_c γ e^{-τ* }

Here, I_c represents the photospheric continuum intensity evaluated at the layer where the continuum optical depth reaches unity at the specified wavelength and the meanings of other parameters have been introduced above. For disk-center spectra, the relative line depth of an absorption line is defined as, d_0 = (I_c - I_λ)/I_c; while for flash spectra obtained during eclipse conditions, the relative line height of an emission line is defined analogously as h_0 = (I_λ - I_c)/I_c. Applying these definitions to the two cases above yields:

Case (1): d_0 = 1 - e^{-τ }
Case (2): h_0 = γ (1 - e^{-τ })

To derive d_0, we applied the first-order approximation e^{-τ} 1 - τ. Next, we obtain an expression for the ratio of the relative line height to the relative line depth: ${}_0$ = h_0/d_0 = γ (τ /τ) = γ . Both I_c and γ are directly measurable from the observed spectra. In our data, we find I_c 9,276,020 cts and γ 0.0028, where γ is primarily determined by the local modulation of the lunar limb profile at the time of spectral acquisition. The ratio ${}_0$ effectively removes the average opacity per unit path, which corresponds to the integration of local opacity along the line of sight, normalized by the geometrical path. What remains is the geometric path scaling factor, , which accounts for the difference in path geometry between the vertical, dense disk-center path and the tangential, sparse off-limb path. It is reasonable to assume that remains constant for all spectral lines formed between the upper photosphere and the low chromosphere. The ratio ${}_0$ increases monotonically with S_λ. Thus, by investigating the ratio ${}_0$ for spectral lines formed at different heights, we can infer variations in the source function. The source function S_λ can be expressed as [**?**]: S_λ = $\beta\lambda$ $B\lambda$(T_e), where B_λ(T_e) is the Planck function at the electron temperature under local thermodynamic equilibrium (LTE), and β_λ represents a non-LTE departure factor. Non-LTE effects are relevant for lines like the Mg I b lines, whose cores form under conditions where photon loss significantly impacts the source function [**?**, **?**].

5. Results and Discussion

Figures 3 and 4 illustrate the spatial intensity distribution patterns of photospheric and chromospheric emission lines and the coronal line Fe XIV 5303 Å, as discussed in Section 3. These patterns reflect the combined effects of the field-of-view positioning and terrestrial scattering. Our field-of-view was located approximately 0.04 R above the solar limb, within the innermost corona. At this height, relatively lower atmospheric lines originating from the photosphere and chromosphere are not emitted locally but appear in the off-limb spectrum due to scattering in the Earth' s atmosphere. This scattering process, which also introduces Baily' s beads, redirects light from the lower solar atmosphere into the field-of-view. The intensity of singly scattered light, I_λ,sca^*, is described by Equation (4), and includes a geometric dilution factor of $1/4\pi r^2$, where r is the distance from the source to the scattering point. The source is fixed, while the scattering point lies in the observation region. From the observer' s perspective, r increases with observed height away from the limb, because the relationship between r, observed distance above the limb h and the distance from the source to the observer at the limb (when h = 0), d_0, is simply related by the trigonometric formula: $r^2 = {d_0}^2 + h^2$. This causes the intensity of scattered lower-atmospheric lines to decrease with distance, producing a fading trend, particularly visible as a gradient from the lower right corner of the image. In contrast, the Fe XIV 5303 Å line is emitted locally in the hot coronal plasma at this height and is thus unaffected by terrestrial scattering. As a result, it exhibits a more uniform spatial distribution and does not show the same radial decline. Figure 4 demonstrates this effect by comparing the flash and on-disk spectra recorded by spatial pixels No. 4 and No. 25. While the on-disk spectra are nearly identical in intensity at these two spatial pixels, the corresponding flash spectra differ significantly in their emission line strengths. The reduced intensity from scattered lower atmospheric lines at this coronal height enables the detection of the intrinsically weak Fe XIV 5303 Å coronal line, typically visible only during totality when recorded using a slitless spectrometer, which lacks spatial selection. If the observation had been made closer to the limb, where scattered light is more intense or local lower-atmospheric emission dominates, the coronal line would likely have been obscured.

As shown in Figure 6, except for a single coronal emission line (Fe XIV 5303 Å), the line-center wavelengths in the flash spectrum closely match those in the disk spectrum, indicating a correspondence between the two. However, their amplitudes differ, as absorption features in the disk spectrum appear as emission features in the flash spectrum, though their relative intensities vary. The lower panel shows that when examining the individual relative line depths (d_0) or heights (h_0) separately, no clear or systematic trend can be observed. The values of these quantities are significantly influenced by the specific spectral line being observed. Strong absorption is observed across multiple spectral line categories, and higher formation heights do not consistently correspond to more pronounced emission. For example, certain Fe II lines (e.g., 5198 and 5235 Å) exhibit relative line heights similar to those of lines formed in deeper atmospheric layers. Mg I lines consistently show strong behavior in both emission and absorption. The values of both quantities are dependent on the spectral line because each incorporates opacity terms, specifically the mean opacity per path, as shown in Equation (4). These opacity terms are closely related to the elemental abundance and excitation potential of the corresponding spectral line, as they influence the opacity by determining the number density of atoms in the lower atomic levels. Since opacity scales with the lower-level number density, it can vary significantly between different atoms. Additionally, the population of neutral atoms in the lower energy states can be affected by processes such as UV overionization, which reduces the number of neutral atoms and thus lowers the opacity, leading to weaker line intensities [**?**, **?**, **?**]. Consequently, the observed differences in relative line depth or height are largely due to variations in the number of atoms responsible for the observed lines along the line of sight.

On the other hand, only the chromospheric lines, such as Mg I and Fe II, exhibit enhanced relative line height compared to the relative line depth of their disk counterparts ($_0$ > 1). In contrast, most other photospheric lines show either comparable values or the opposite trend. This pattern needs further analysis of the quantities h_0 and d_0 for selected lines, categorized by atmospheric height. The spectral parameters, h_0, d_0, and $_0$ are summarized in Table 1, with the trends visualized in Figure 7. In Table 1 and Figure 7, when examining individual relative line depths (d_0) or heights (h_0) separately, no clear or systematic dependence on formation height is observed, meaning there is no obvious correlation with the general category of the line’ s origin within the solar atmosphere. The reasons for this are outlined above. We noticed that a more systematic formation-height dependent pattern emerges when analyzing the ratio $_0$. As shown in Figure 7, measured ratios across the three spectral categories exhibit distinct trends (see Table 1): lines of category I consistently show $_0 > 1$, with several Fe II lines reaching values around 2; lines of category II have ratios close to 1, while lines of category III exhibit $_0 < 1$. To understand the physical significance of $_0$, we refer to its theoretical form in Equation (7), which results from the division of the two terms in Equation (4). As previously mentioned, this formulation removes the mean opacity per path, which varies largely between different spectral lines. By using the ratio $_0$, we effectively minimize the opacity effects, allowing us to isolate variations in the source function. Our observations in Figure 7 show that the source function is strongest for the chromospheric lines, particularly Fe II lines, moderate for the photospheric low FIP element lines, and weakest for the photospheric neutral atom lines. The source function can be expressed as S_λ = $\beta\lambda$ $B\lambda$(T_e) as shown in Equation (8). Although we have not directly measured the exact values of the source function, the relatively observed trend suggests the source function increases with formation height. This is qualitatively consistent with predictions from atmospheric models, such as the VAL model [**?**], which indicate that the electron temperature rises with height. Additionally, previous eclipse observations have shown that chromospheric emission lines can become unusually strong near active regions. This effect is likely due to intensified ultraviolet radiation fields, which influence both line intensities and the source function [**?**, **?**, **?**]. Given the nature of these processes and the challenges in identifying active regions in our dataset, the exact physical origin of the observed increase in the source function with height, especially for Fe II lines, remains unclear.

In summary, our observations reveal several key findings: (i) The spatial intensity distribution patterns observed in the flash spectrum arise primarily due to Earth atmospheric scattering effects, as the field-of-view is positioned approximately 0.04 R above the solar limb. This positioning captures the innermost corona while also being affected by scattered photospheric and chromospheric light, leading to the presence of lower atmospheric spectral lines in the spectrum. The intrinsically weak coronal line, like Fe XIV 5303 Å, becomes visible due to the reduction in scattered light at this height. (ii) When the disk and flash spectra are analyzed separately, it becomes evident that the relative line depths d_0 and heights h_0 do not show a straightforward correlation with formation height. While these low level lines basically share a similar geometrical light path, the variation in these quantities is primarily due to variations in opacity, which depend on atomic number densities and are sensitive to non-LTE conditions. (iii) By comparing flash and disk absorption spectra, we find that the ratio ${}_0$ reveals a clear formation-height-dependent pattern across spectral lines. This ratio minimizes opacity effects and serves as an indicator of intrinsic source function variations in the solar atmosphere. (iv) Using the ratio ${}_0$ as an indicator for the source function, we find that it generally increases with formation height, with chromospheric lines, especially Fe II, showing the highest values. This trend likely reflects rising electron temperatures with height, consistent with certain atmospheric models. However, flash spectra observed near chromospheric active regions suggest that locally enhanced radiation also raises the source function.

6. Conclusions

The flash spectrum acquired during the total solar eclipse of 2013 November 3 was analyzed to investigate the spectral line behavior within the solar atmosphere, with a focus on line-center intensities. We positioned the field-of-view approximately 0.04 solar radii above the east limb, close to the second contact point. The flash spectrum captures a range of spectral lines originating from the lower atmosphere, including the upper photosphere and lower chromosphere, while also detecting the coronal line Fe XIV 5303 Å. Terrestrial scattering plays a significant role in allowing emission from different atmospheric layers to appear in a single observational frame. The presence of Baily’ s beads near our field-of-view introduces scattered light from the remaining photosphere, bringing both photospheric continuum and numerous emission lines from the extreme photosphere into the observed spectrum. Additionally, emission lines from the lower chromosphere are also scattered into the observed spectrum. Consequently, due to our observing position, the local coronal line Fe XIV 5303 Å coexists with the scattered components.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC) under grant Nos. 12473054 and 12127901, the Strategic Priority Research Program of the Chinese Academy of Sciences under grant No. XDB0560000, Yunnan Key Laboratory of Solar Physics and Space Science under No. 202205AG070009, and Yunnan Fundamental Research Projects under No. 202105AC160085.

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