Helium shells and faint emission lines from slitless flash spectra

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Abstract At the time of the two last solar total eclipses of August 1st, 2008 in Siberia and July 11th, 2010 in French Polynesia, high frame rate CCD flash spectra were obtained. These eclipses occurred in quiet Sun period and after. The slitless flash spectra show two helium shells, in the weak Paschen α 4686 Å line of the ionized helium HeII and in the neutral helium HeI line at 4713 Å. The extensions of these helium shells are typically 3 Mm. In prominences, the extension of the interface with the corona is much more extended. The observations and analysis of these lines can properly be done only in eclipse conditions, when the intensity threshold reaches the coronal level, and the parasitic scattered light is virtually zero. Under the layers of 1 Mm above the limb, many faint low FIP lines were also seen in emission. The solar limb can be defined using the weak continuum appearing between the emission lines at the time of the second and third contact. The variations of the singly ionized iron line, the HeI and HeII lines and the continuum intensity are analyzed. The intensity ratio of ionized to neutral helium is studied for evaluating the ionization rate in low layers up to 2 Mm and also around a prominence.

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Introduction

Flash spectra are known for a long time [1]. Recently, observations of flash spectra were carried out by different observers at total solar eclipses using a CCD camera [2] and flash spectra experiments using optical fibers were made for polarization analysis [3]. During our observations, we performed a high cadence CCD slitless spectra in the region of the neutral helium He I 4713 Å line and of the ionized helium He II 4686 Å line, with the aim of studying the top of the photosphere and the chromosphere to corona transition region [4]. These flash spectra were obtained at the total solar eclipses of 1st August 2008 and 11th July 2010 [5] using about the same blue spectral range. The duration of each analyzed sequence is about 10 s, taken around each internal contact. Fast CCD imaging is used (15 frames/s). Eclipse conditions allow to reach a negligible level of parasitic scattered light; indeed coronal levels are easily reached during the observations [6,7].

KEYWORDS
Total solar eclipse; Chromosphere; Flash spectra; Helium shell; Solar transition region; Low FIP emission lines
The second goal of these observations is the analysis of the helium shells in layers near and above the limb at a 1 Mm height. This is impossible to do such observations outside eclipses’ conditions because the solar disk irradiates the instrument. We also recorded many faint emission lines at the solar edge, seen superposed to the continuum. This continuum corresponds to Baily’s bead spectra revealing the extreme limb of the photosphere when the Moon limb finally covers entirely the solar disk. Prominences can also be studied. Flash spectra were already analyzed in the past using photographic observations [1,8] but at a lower rate, making their quantitative analysis difficult.

CCD flash spectra were also obtained during the July 22nd 2009 total eclipse [4,6], but in another spectral range of 4490–4620 Å (see Fig. 6). The analysis of the 2009 results are beyond the scope of this paper and will be published later along with additional studies of the low layers of the transition region and the chromosphere.

Observations and image processing

We used a 600 grooves/mm transmitting grating placed in front of a 600 mm focus length achromatic objective, and a 12 bit CCD Lumenera fast camera (USB-2) imaging the spectra at a cadence of 15 frames per second at the time of the contacts, before and after the totality [5,9]. The corresponding spatial resolution on a radial direction corresponding to two contacts, before and after the totality is reached showing many faint emission lines at the extreme limb and, simultaneously, the extreme photospheric continuum with F-lines. This analysis is done thanks to the Moon limb and, simultaneously, the extreme photospheric limb continuum with F-lines. This analysis is done thanks to the Moon motion (0.54 arcsecond/s) over the solar limb, mountains and valleys of the Lunar profile modulating the solar edge.

A second ionized helium shell in the He II 4686 Å line was first evidenced during the August 1st 2008 total eclipse. We accurately analyzed the light curves deduced from intensity measurements of the flash spectra (see Fig. 3), taking into account the lunar profile that modulates the intensity of the lines. We averaged and measured the fluxes in the corresponding lunar valleys.

We stacked and aligned 6 spectra every 3 spectra using the Iris software [10] in order to increase the signal to noise ratio (along Nyquist frequency rule). The resulting averaged height sampling is 75 km near the solar edge. We compared one single image and the resulting image of the 6 stacked aligned spectra and found that the resulting smearing is negligible when intensity levels are properly adjusted. We checked that there was no shift in horizontal and vertical directions during the alignments and during the stacking process.

Steps above a height of 1600 km over the limb were 75 km and they correspond to 6 stacked spectra taken every 3 spectra. Below 1600 km we used a smaller step value because the intensity levels of some Baily’s bead spectra were 10–100 times higher and even close to the saturation level at altitudes below 1000 km. During that acquisition process, the cadence of the frame rate was reduced to approximately 9 frames/s to avoid saturating spectra.

The intensity ratio of He II/He I along the shells as a function of the heights above the limb was analyzed. This analysis was done in order to compare the ionization rate in the low layers of the transition region, and in the prominence to corona interface in higher layers [7]. Fig. 4 shows the analysis performed in these two solar regions.

We also studied what we call the “true” solar edge as observed between a forest of faint emission lines. We looked at the intensity profiles as a function of wavelength for different times near the second contact of the 2010 total solar eclipse (see Fig. 5). We also analyzed the continuum corresponding to Baily’s bead spectra and, simultaneously, the Fe II 4629 Å line intensity, in order to determine the solar edge profile (see Fig. 6). Each flux measurement shown in Fig. 6 was taken from a single spectrum, without stacking spectra. The continuum seen between the helium prominences and the prominence to cavity regions [9] is then measured.

Results and discussion

We evaluated the intensity of the continuum from the solar edge between faint emission lines and of Fraunhofer lines above the solar edge, as seen without the parasitic scattered light of usual observations done outside of total eclipses. This measurement could also be relevant to the determination of the solar diameter (work in progress), using the eclipse method [11] and taking the lunar diameter as a reference.

The faint emission lines recorded at the bottom of the chromosphere which do not correspond to F-lines, could contribute to a new definition of the solar edge, and to the analysis of the structuration of the low layers of the transition region due to the increasing influence of the magnetic field emerging from the photosphere. The terminology “reversing layer” which was used in the past should indeed be revised, taking into account observations of high cadence CCD flash spectra.

Fig. 3 shows the intensities profiles deduced from the sequences of flash spectra. The continuum intensity light curves are modulated by the mountains and valleys on the Moon limb. They decrease rapidly at the beginning of the totality (see Fig. 2). The intensity profiles are all fitted with an exponential decay and plotted in log scale for a better estimation of the gradient (see Fig. 3). The lower slope of the helium lines variation indicates a higher temperature than the one of the Fe II line which is formed at heights below or near 0.8 Mm corresponding to the new minimum of temperature as proposed by Fontenla [12]. This Fe II line, like many other emission lines observed in this “mesospheric” region, are characterized by a low First Ionization Potential (FIP), see Figs. 1 and 7. These results show that low FIP lines are very abundant in the low layers of the transition region. The FIP is lower than 10 eV for most of metallic elements.

We define the “mesospheric” layer as the part of the solar atmosphere situated above the quiet uniform top of the photosphere (near the minimum of temperature which is not far from the visible edge of the photosphere in the continuum) and where the corona does not yet dominate. It is a mixing of cool neutral gas, of hot neutral and of ionized gas (under the more dynamical chromosphere) and of coronal plasma penetrating deep in the chromosphere.
The exponential decays curves are fitted for the He II 4686 Å and He I 4713 Å lines and their equations are given in Table 1. The differences of gradients between He I 4713 Å and He II 4686 Å intensities profiles were difficult to evaluate in the past [13]. Thanks to the 2010 total eclipse slitless spectra, we could look for a definite difference between the helium lines showing a higher temperature for the He II line than the one of the He I. Indeed, the ionization potential of He II Paschen α is 54 eV, and it is 24 eV for the He I line.

The lower gradients values of 0.0013 for He II and 0.0018 for He I lines indicate a higher temperature across the shells. The gradient of 0.0025 for the Fe II line corresponds to a lower temperature than the ones of helium; the excitation potential of the Fe II at 4629 Å is 5.48 eV. This Fe II low FIP line completely disappears above 1.8 Mm; the helium lines are also seen above 2.2 Mm.

The radial intensity variations of Fig. 3 are nevertheless almost in agreement with what was known for the He I shell from the D3 bright line [14] and from the half-width measurements of the D3 line between 1.5 and 4.5 Mm, including spicules and group of spicules [15]. The second ionized helium shell, in the He II 4686 Å line, corresponds to higher temperatures layers where the corona penetrates [16,17]. The analysis of the helium temperature can be done by studying the inten-
sity ratio of He II/He I. Near the edge of a prominence, as shown on Fig. 4, it partly reflects the increase of temperatures when going upwards to the corona at a 25 Mm height from the limb. The intensity ratio of He II/He I allows to compare the ionization rate of helium. It increases apparently more rapidly in the low layers of the transition region (below the 2 Mm heights) than in the upper layers between 23 and 28 Mm corresponding to the prominence to corona interface.

The intensities and fluxes of the continuum and of faint emission lines are plotted in Figs. 5 and 6, and show what we could define the “true” solar edge, seen without parasitic scattered light coming from the disk. The low FIP lines profiles, like the Fe II 4629 Å line, modify the solar edge intensity profile. The observed pseudo-continuum in Fig. 5 could correspond to the superposition of several low FIP lines profiles, some of them not resolved.
On the last graph of Fig. 5, we compare the area under faint emissions lines with the corresponding pseudo-continuum – presumably without lines – for evaluating the time of the contact. The Baily’s bead spectrum of Fig. 7, indicating selected lines of low first potential, corresponds to the top of the photosphere. In Fig. 6, fluxes that are lower than $10^{-3}$ units of the solar disk brightness per Baily’s bead size in Mm, at the end of contact, could be due to Thomson scattering. At this level, the photospheric continuum almost completely disappear, leaving place for the corona to penetrate.

Fig. 5 Spectral intensities for several heights above the limb deduced from flash spectra taken at the time of the second contact. They show many faint resolved and unresolved mesospheric low FIP lines (from the total solar eclipse of 11 July 2010 in French Polynesia), see also Fig. 2.
Many low FIP emission lines are created in the solar mesospheric layer, below and above 0.4 Mm height where the magnetic field is emerging into the coronal plasma. Ionized and neutral helium lines are seen at 0.4 Mm height up to 2.2 Mm and further out at lower intensity. The intensity ratio of ionized over neutral helium, seen in low layers close to the limb,
reveals an ionization process different from what is observed in the prominence to corona interface, where the medium is probably less collisional. It is yet not clear whether these ionized helium lines are indeed produced in the low layers of the transition region, close to the limb, where low excitation emission lines of low FIP elements are produced, or only in upper layers seen along the line of sight due to overlapping effects. They could also be produced in inter-spicule regions where the hotter coronal plasma penetrates, and where the helium line could probably be ionized by photo-excitation by the coronal UV and EUV light. The heating process is badly known but could be “associated” with the emergence of the magnetic field in dynamical structures. We expect new improved data from the next total eclipse of November 13th 2012.

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