SF2A 2014
J. Ballet, F. Bournaud, F. Martins, R. Monier and C. Reylé (eds)

THE PHOTOSPHERE-CORONA INTERFACE: ENRICHEMENT OF THE CORONA IN LOW FIP ELEMENTS AND HELIUM SHELLS

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Abstract. Slitless consecutive spectra were obtained during the contacts of the last total solar eclipses (2008, 2009, 2010, 2012, et 2013). They allowed to show that the overabundance of low First Ionisation Potential (FIP) elements (Fe II, Ti II, Ba II) in the corona comes from the low layers of the solar atmosphere, just near and above the temperature minimum region of the high photosphere. All spectra are recorded with a fast CCD/CMOS camera, with an equivalent radial resolution of 60 milliarcseconds, or 45 km in the solar atmosphere, above a solar edge not affected by the parasitic light like it is outside of total eclipse conditions. Many emission lines of low FIP elements appear in regions situated between 200 to 600 km above the solar limb defined by the true continuum measured between the lines. This continuum appears at these altitudes where the beta of the plasma is near 1. The He I 4713 Å and He II 4686 Å (Paschen alpha line) shells appear at the height of 800 km above the solar edge and higher. The light curve $I = f(h)$ of each ion is located at a particuliar altitude in the solar atmosphere. The scale height corresponds to a density variation, which allows to evaluate the temperature thanks to the hydrostatic equilibrium assumption. Moreover, with ionised Titanium lines taken as markers, we show a similarity between the photosphere-corona interface and the prominence-corona interface. We discuss the role of the magnetic field and the ambipolar diffusion for supplying the corona in mass, without taking into account the role of spicules. The photo-ionisation of the helium lines by the EUV coronal lines is illustrated thanks to an extract of SDO/AIA coronal stacked image simultaneously obtained.

Keywords: solar photosphere-corona interface, first ionisation potential, FIP, temperature minimum, loop prominence, chromosphere-corona transition region, interspicule region

1 Introduction

We report on the analysis of slitless flash spectra obtained at the 22 July 2009 solar total eclipse using a fast CCD camera taking frames at a rate of 15 images/second and a 12 bit dynamic range. The flash spectra are seen as many thin crescents, corresponding to the myriad of emission lines originating from the photosphere/chromosphere-corona interface. The edge of the Moon is used like a natural occulter of the solar limb, allowing to explore the regions situated from the low photosphere (extreme-limb) to the chromosphere without parasitic light coming from the solar disk. The radial resolution is 45 km after having stacked 6 spectra every 3 spectra and the spatial resolution is 1150 km/pixel in azimuthal direction where some structuration from macrospicules and inhomogeneities begin to be resolved in the image of the He I 4471 Å high FIP line.

2 Analysis and emission line identification

We performed intensity measurements in the monochromatic emission line images. Figure 1 illustrates two extracts of flash spectra, where a myriad of emission lines like the line of Titanium, Ti II 4468 Å, which is used as a marker for the interfaces analysis. At left we indicate the correspondance between the lunar profile with mountains and valleys and the shape of the emission lines (profile of the Moon prepared by P. Rocher from IMCCE). We selected this Ti II 4468 Å ion for localizing a low FIP element at low altitudes, close to the

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temperature minimum, going to higher altitudes at the extremity of the monochromatic crescent image. Figure 1 shows a monochromatic image of a loop prominence in the same Ti II 4468 Å low FIP line as the one seen at lower altitudes in the photosphere-chromosphere interface. This suggests that some low FIP elements could supply mass in the chromosphere-corona transition region, where the prominence are seen. We used also results coming from the last 3 November 2013 hybrid total eclipse for analyzing more precisely the correspondence between the Baily's Bead in spectra, the low FIP lines emissions, and the lunar profile, see Figure 2.

The light curves in Figure 3 allow to separate the continuum from the low FIP Fe II ion emission.

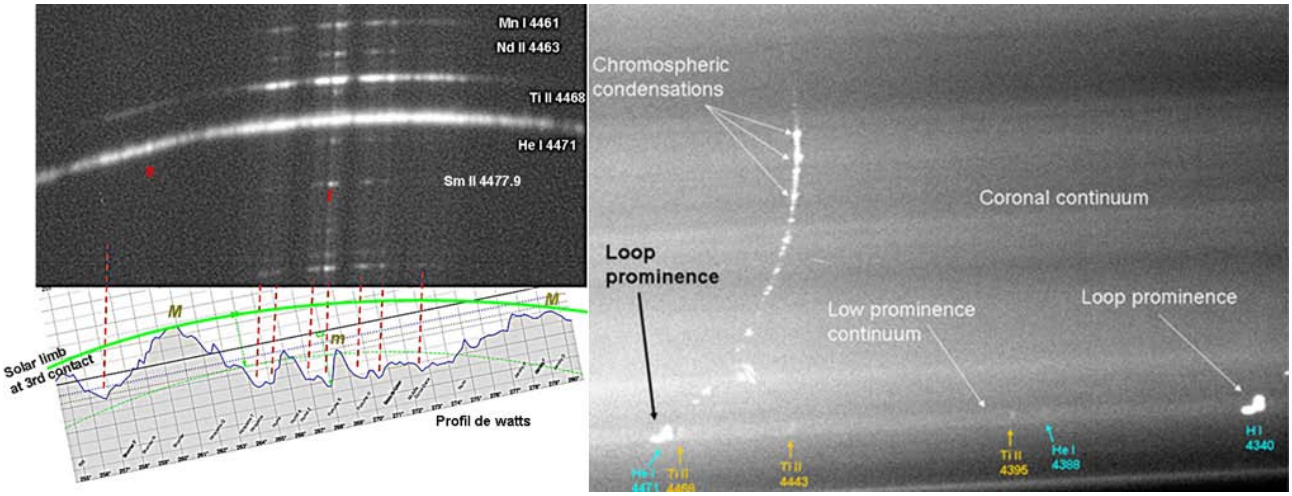

Fig. 1. Extract of flash spectra at the third contact (end of the totality) of the 22 July 2009 total solar eclipse. At left, low FIP emission lines and the helium shell He I 4471 Å seen as crescents. 18 stacked and aligned spectra corresponding to altitudes ranging from 1550 to 1780 km in the radial direction. At right, 50 stacked and aligned spectra before the third contact performed to increase the signal to noise ratio, at the averaged altitude corresponding to 7000 km above the solar limb. The coronal continuum corresponds to the narrow bright bands. At the extremity of the He I 4471 Å shell, some chromospheric condensations appear (some other are small prominences) but no correlation with the coronal continuum bands is evident. Note the Ti II 4468 Å, Ti II 4443 Å and Ti II 4395 Å monochromatic images of the loop prominence which are seen at the end of the crescent producing a band in the continuum.

3 Helium shells and low FIP lines in the low interface region

The analysis of the flash spectra shows the helium shells (He I 4713 and He II 4686) and low FIP lines like the line of the Fe II 4629 Å appearing at lower altitudes, below 800 km, close to the temperature minimum region, see Figure 3. By using the AIA/SDO images taken at the same time as the eclipse totality, we compared the same east solar edge in the 193 Fe XII line with the one of the flash spectra at the same scale, see Figure 4. This allows to compare the shells extension, by comparing the optically thin rather cool lines in the visible (see Hirayama & Irie 1984), and the low corona EUV lines of Fe XII at 2 MK at the solar edge. The dark thin features are spicules seen in absorption, corresponding to cool plasma. They appear close to the EUV limb, at height below 5 Mm, corresponding to the He shell extension.

4 Discussion and Conclusions

The identification of the low FIP element Ti II simultaneously seen in the photosphere-chromosphere/corona interface and in the prominence-corona interface suggests that this element could have been guided or transported by the presence of the magnetic field. The magnetic field is responsible of the inhomogeneities, seen in the macrospicular region. The structuration of the low altitude layers where each ion is created and of the continuum at 4500 Å at separated layers, suggest some effects of ambipolar diffusion occuring in the interspicular medium. The separation between the continuum and the low FIP lines in the region of the temperature minimum could be due to the temperature bifurcation, where the elements begin to be ionised.

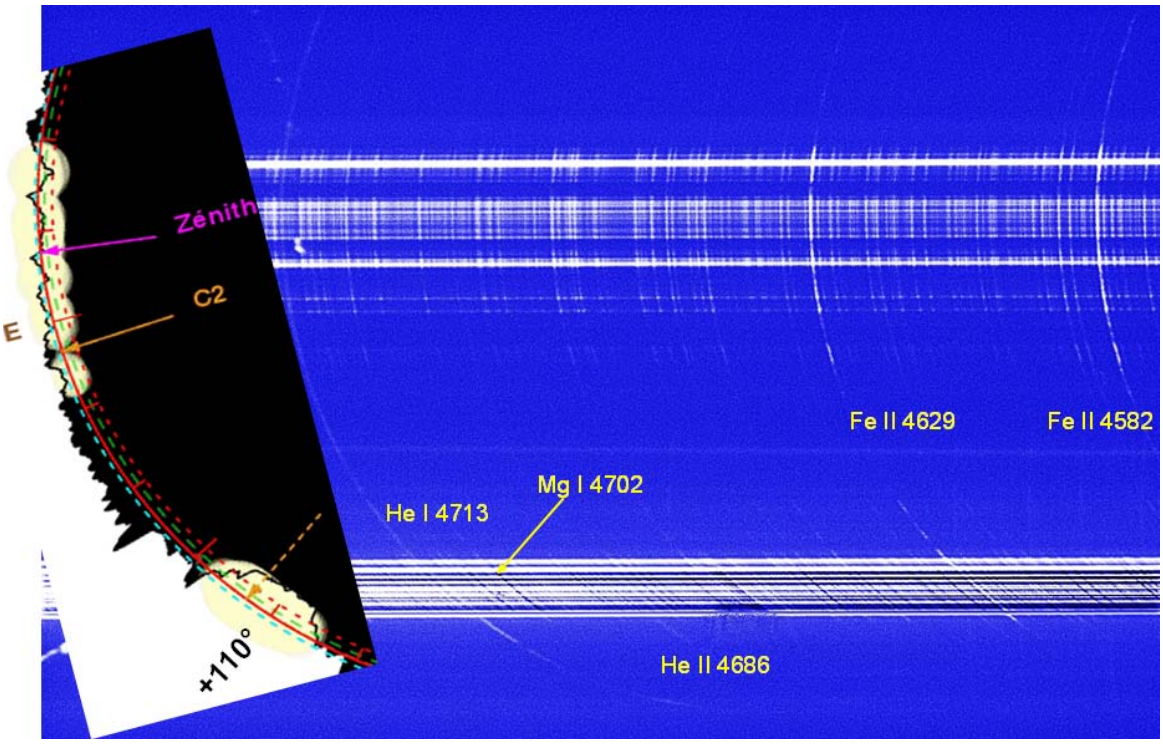

Fig. 2. Baily's Bead continuum in spectrum and emission lines limited by the Lunar profile (cartoon at left from Xavier Jubier) on the flash spectra from the last total hybrid eclipse of 3 November 2013 (Uganda): Helium shells of He I 4713 Å and of He II 4686 Å observed in extension towards the polar regions, and appearing in lower layers (h = 800 km); brightenings from the low FIP elements lines.

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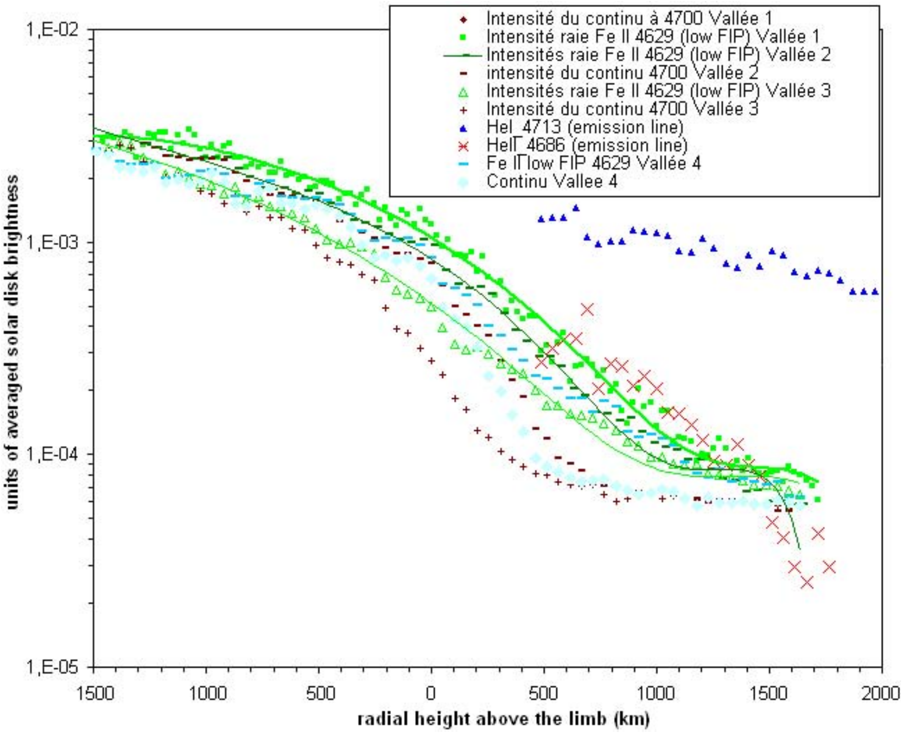

Fig. 3. Light curves using successive spectra where the true continuum (without parasitic light) is isolated from the many low FIP emission lines shown with different colours. The light curves come from the sequence after removing the neutral density filters used to reduce the light before Baily beads appear.

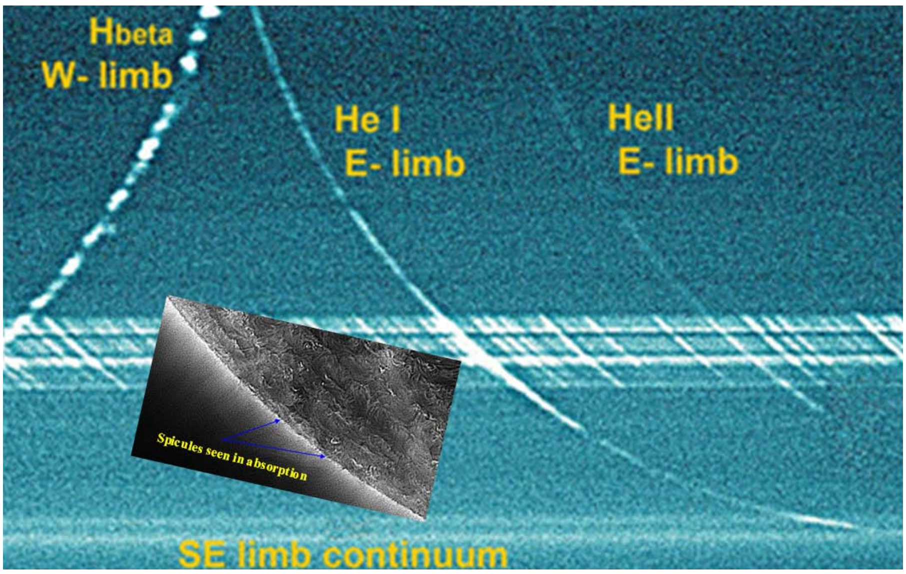

Fig. 4. New flash spectra from the total hybrid eclipse of 3 November 2013 (Uganda): Helium shells (He I 4713 Å and He II 4686 Å) observed in a larger extension towards the polar regions, and appearing in lower layers ($h < 800$ km): brightening of the low First Ionisation Potential elements. Inserted is an AIA image at 193 Å in the same field of view as the flash spectra during the 3 November 2013 total eclipse (14h13 to 14h25 TU), 13 images in the same region as flash spectra have been stacked and processed (unsharp masking). The spicules are seen in absorption (dark). At higher altitudes, the jets and loops appear in emission. Note that they are not the prolongation of spicules at higher altitude, but they could be new magnetic structures heated at 2 MK.