Solar Phys (2010) 264: 45–55
DOI 10.1007/s11207-010-9575-7

A Comparison of the Red and Green Coronal Line Intensities at the 29 March 2006 and the 1 August 2008 Total Solar Eclipses: Considerations of the Temperature of the Solar Corona

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Received: 30 October 2009 / Accepted: 12 May 2010 / Published online: 5 June 2010

Abstract During the total solar eclipse at Akademgorodok, Siberia, Russia, on 1 August 2008, we imaged the flash spectrum with a slitless spectrograph. We have spectroscopically determined the duration of totality, the epoch of the second and third contacts and the duration of the flash spectrum. Here we compare the 2008 flash spectra with those that we similarly obtained from the total solar eclipse of 29 March 2006, at Kastellorizo, Greece. Any changes of the intensity of the coronal emission lines, in particularly those of Fe X and Fe XIV, could give us valuable information about the temperature of the corona. The results show that the ionization state of the corona, as manifested especially by the Fe XIV emission line, was much weaker during the 2008 eclipse, indicating that following the long, inactive period during the solar minimum, there was a drop in the overall temperature of the solar corona.

Keywords Corona · Duration of totality · Duration of flash spectrum · Eclipses · Ionized iron

1. Introduction

We have studied, with a slitless spectrograph, the flash spectrum emission lines of Fe X and Fe XIV, during two solar eclipses: the total solar eclipse of 29 March 2006 observed at the island of Kastellorizo, Greece, and the total solar eclipse of 1 August 2008 at Akademgorodok (near Novosibirsk), Siberia, Russia (Pasachoff *et al.*, 2007, 2009). The Sun was fairly active

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during the 2006 eclipse. In contrast, it was quiet and inactive during the 2008 eclipse, and for a very long interval before the eclipse. Any changes of the emission lines between the two epochs could be directly attributed to changes in the activity of the Sun (Esser *et al.*, 1995; Kanno, Tsubaki, and Kurokawa, 1971; Singh, Gupta, and Cowsik, 1997; Brickhouse, Esser, and Habbal, 1995; Singh *et al.*, 1999; Pasachoff, 2009a, 2009b; Golub and Pasachoff, 2009).

2. The 1 August 2008 Total Solar Eclipse at Akademgorodok, Russia

The observations of the 2008 total solar eclipse described herein (Figure 1) were undertaken at the roof of the Budker Institute of Nuclear Physics, in Akademgorodok, near Novosibirsk, in southern Siberia, Russia. At that location ($\lambda = 83°06'43''.8$ E, $\phi = +54°50'57''.1$), the maximum of the eclipse occurred at 10:45:36.5 UT.

2.1. The Slitless Spectrograph used during the 2008 Eclipse

In order to record the flash spectrum, a slitless spectrograph with a reflection grating of 300 lines/mm, blazed at 5000 Å, and an 135 mm f/3.5 telephoto lens was constructed by one of us (A.V.).

The system's efficiency was about 60% at 5303 Å (Fe XIV emission line) and 20% at 6374 Å (Fe X emission line). The grating was placed before the telephoto lens on a rotating turntable that allowed the rotation of the grating. The full range of the visible spectrum, from 3900 Å to 6700 Å, was projected on the CCD sensor of the digital camera. The resolution of the spectrograph was 1.5 Å/pixel at 5890 Å. The diameter of the Sun corresponded to 275 pixels or 6.87″/pixel. With the help of the turntable, the direction of the grating lines could be set parallel to the direction of the last visible elongated crescent of the Sun; this narrow crescent played the role of the "slit" in the slitless spectrograph. The solar light was directed to the spectrograph by a simple reflection coelostat (Veio, 1977; Dougherty, 1982; Demianski and Pasachoff, 1984; Pasachoff and Livingston, 1984), which was also constructed by one of us (A.V.).

2.2. The Flash Spectrum of the Total Solar Eclipse of 1 August 2008

Data were recorded during the ingress and egress phases. However, the ingress data were underexposed. They were mainly used for adjusting the exposure time of the egress phase.

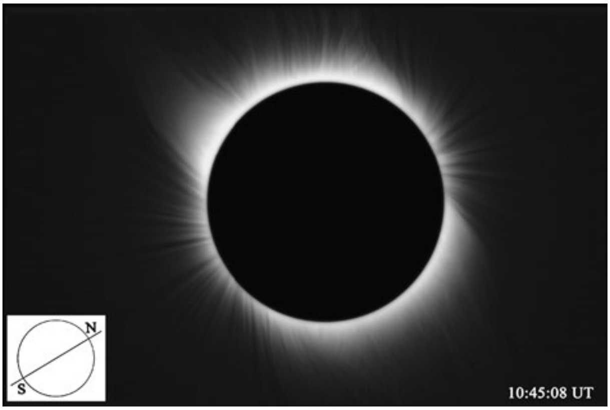


Figure 1 The inner and the outer corona during the total solar eclipse of 1 August 2008, shown in a composite of seven of our images to flatten the dynamic range. The solar rotation axis is depicted in the inset at the lower left corner.

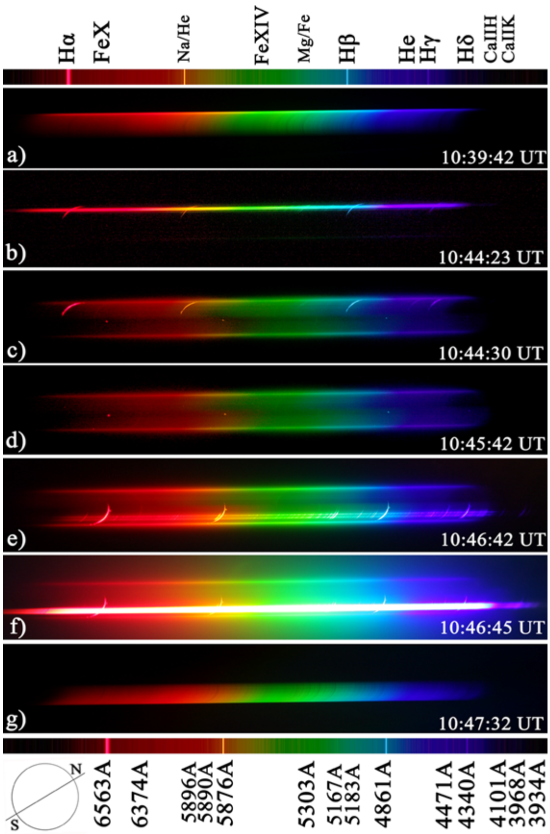


Figure 2 Solar spectra during the partial phases (a and g), a few seconds before (b) and a few seconds after (c) second contact, during the mid eclipse (d), a few seconds before (e) and a few seconds after (f) third contact.

They proved very useful for estimating the duration of totality and the exact time of second and third contact. A sequence of 91 spectra (some of which are presented in Figure 2) were recorded during totality and the partial phases, with ∼1/50 seconds exposure time.

Among the chromospheric emission lines observed (Figure 3) in the flash spectrum, were emission lines from hydrogen (6562.8 Å), sodium (5890 Å, 5896 Å), helium 5876 Å (the D_3 discovery line), magnesium I “b” (5167.3 Å, 5172.7 Å, 5183.6 Å), neutral and once-

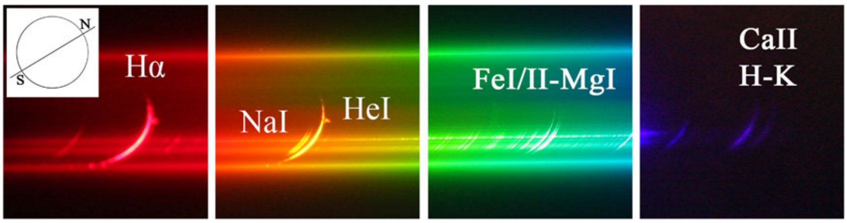


Figure 3 Snapshots of flash-spectrum emission lines from the chromosphere and a prominence.

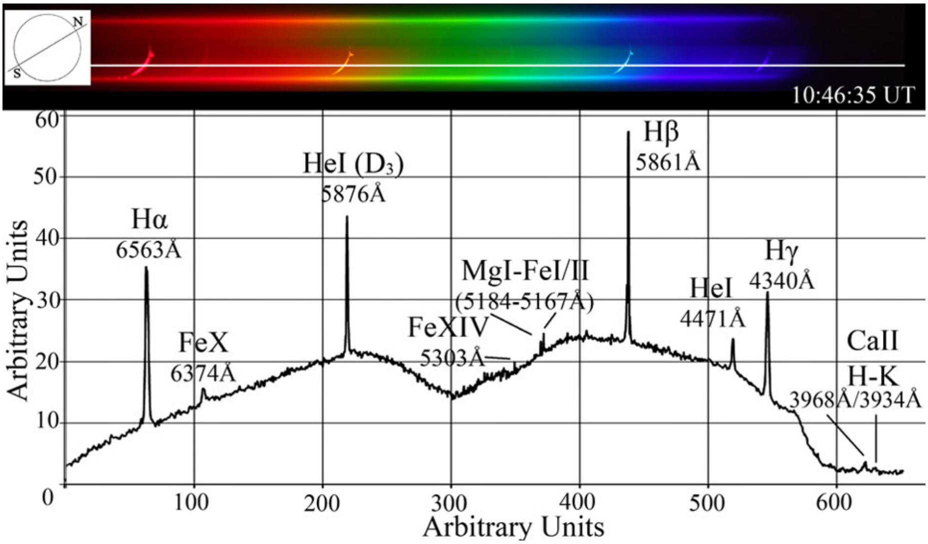
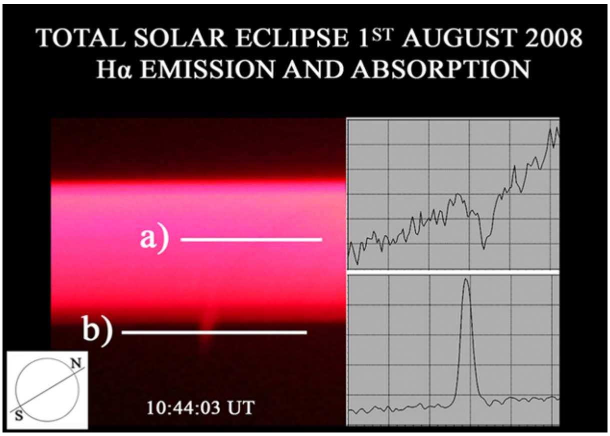


Figure 4 The flash spectrum of the 1 August 2008 total solar eclipse (top) and a cut through it, plotted on a linear scale (bottom). The cut in the bottom panel was taken along the white line in the top panel. The moderate intensity of the Fe X emission line is clearly visible. The extremely weak emission of the Fe XIV line is hardly visible.

ionized iron (5168.9 Å, 5169.1 Å – blended with the magnesium lines) and the H (3968.5 Å) and K (3933.6 Å) lines of once-ionized calcium. (For the origin of the K-line notation, see Pasachoff and Suer 2009, 2010.)

Of the two characteristic coronal emission lines that are produced by the multiply ionized iron in the visible part of the spectrum (Figure 5), the Fe XIV (5302.8 Å) coronal emission line, which requires a temperature of about 1.9×10^6 K, was barely visible, whereas the much lower-temperature (1.2×10^6 K) Fe X (6374 Å) line was clearly visible (Figure 4) (Singh *et al.*, 2002; Takeda *et al.*, 2000).

Figure 5 Before second contact, both emission and absorption lines are observed.



2.3. Spectroscopic Definition of second and third Contact, Totality and the Duration of the 1 August 2008 Flash Spectrum

2.3.1. Spectroscopic Definition of the Duration of the Flash Spectrum, the second and third Contacts, and the Duration of Totality, using the Hα *Emission Line*

The duration of the flash spectrum depends on the geometrical and physical characteristic of the investigated eclipse. In particular, it depends on the angular velocity of the Moon (relatively to the Sun) and the height of the chromosphere, which depends on solar activity. Statistics of spicule height and other parameters were recently re-measured by Pasachoff, Jacobson, and Sterling (2009). Furthermore, the *ingress* and *egress* events are symmetrical only when the center of the disks of the Sun and the Moon coincide during the middle of the eclipse.

Until 10:43:55 UT, the solar spectrum was dominated by absorption lines (Figure 2a). For the next 25 seconds, both absorption and emission lines were present (clearly seen in Figure 5). At 10:44:20 UT the absorption lines disappeared. At 10:44:30.5±0.5 UT, the maximum Hα emission was observed, corresponding to the spectroscopic Hα second contact (Figure 2c). During the next 28 seconds, the intensity of the Hα emission line decreased (while the chromosphere on the east limb was being eclipsed). Between 10:44:58 UT and 10:46:21 UT, no chromospheric Hα emission was observed (but there was strong Hα and He emission from intense prominences in both the east and west limbs). The middle of the eclipse (assumed to be symmetrically centered between second and third contacts) occurred at 10:45:36±2 UT. After totality, chromospheric Hα emission increased (when the chromosphere on the west limb was emerging from eclipse), reaching a maximum at 10:46:43 ± 1 UT (Figure 2e), indicating the spectroscopic Hα third contact. For the next 25 seconds, Hα emission (Figure 2f) gradually decreased, and at 10:47:12 UT, the solar spectrum was again dominated by absorption lines (Figure 2g).

In Figure 6, the intensity of Hα, $\mathrm{H}\alpha = I_\lambda - I_\mathrm{c}$ (where, I_λ is the integrated intensity underneath the Hα line profiles and I_c is the corresponding continuum intensity interpolated either side of the line emission) is presented as a function of time. The intensities were calculated by integrating the data underneath the line profiles. The intensity of the continuum emission was calculated by interpolating the continuum intensity either side of the line emission.

During ingress (east limb of the Sun), Hα and He emission lines were observed in our spectra for 63 ± 2 seconds. During egress (west limb), this interval became smaller, 48 ± 3 seconds (Figure 8). It is not surprising that the two durations are not equal, as the eclipse was not centrally symmetric. The duration of the eclipse (calculated between the two Hα peaks) according to the above measurements was 2 min 12 seconds. During the 83 middle seconds of this interval, no Hα emission was detected (Figure 6).

The online manifestation of Espenak's calculations (http://eclipse.gsfc.nasa.gov/SEmono/TSE2008/TSE2008tab/TSE2008-Table13.pdf) by Xavier Jubier (http://xjubier.free.fr/en/site_pages/SolarEclipseCalc_Diagram.html), shows that at Akademgorodok the second contact occurred at 10:44:26.0 UT and the third contact at 10:46:44.3 UT, with mid-eclipse at 10:45:36.5 UT and a total duration of 2 min 17.3 seconds. Thus, the spectroscopic Hα measurements are 4.5 ± 0.5 seconds later than the prediction of Jubier for the second contact and 1.3 ± 1 seconds earlier than the prediction for the third contact. The duration of the eclipse is 5.3 s shorter than Espenak's calculations, which is significant. However, the mid-eclipse differs by only 0.5 ± 2 seconds, which, in effect, coincides with Espenak's calculations.

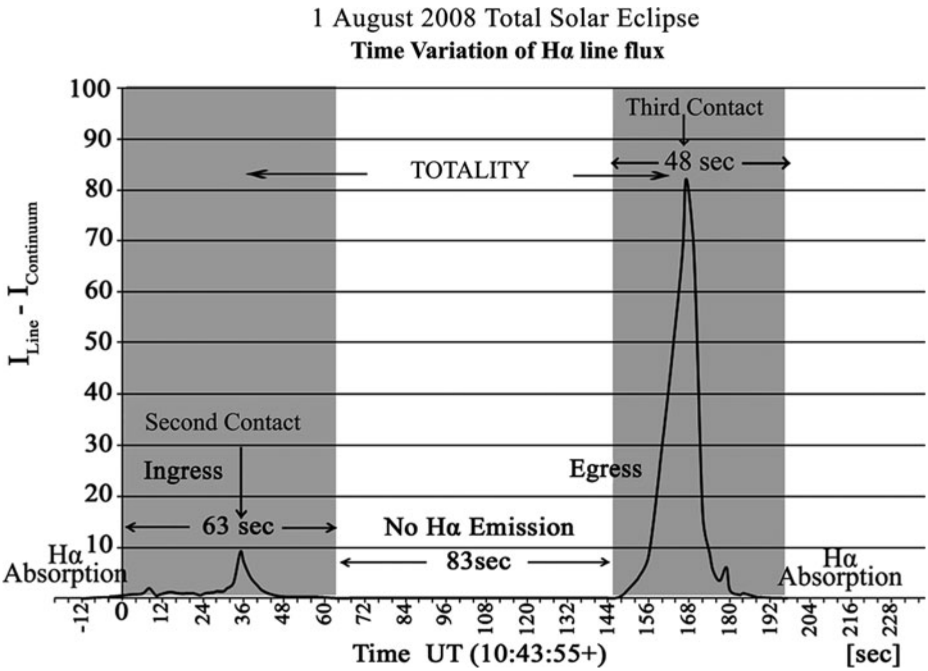


Figure 6 The intensity of the hydrogen Hα line as a function of time. The graph of the Hα intensity during part of ingress is lower, because the corresponding CCD images were underexposed.

2.3.2. Spectroscopic Definition of the second and third Contacts, and the Duration of Totality, Using the Mg I *and* Fe I/II *Spectral Emission Lines*

Among the most characteristic heavy-element emission lines, observed in the solar chromosphere, are those of Mg I b lines (5167.3 Å, 5172.7 Å, 5183.6 Å), Fe I (5168.9 Å) and Fe II (5169.1 Å) in the green part of the spectrum. These are generated by elements in the lower chromosphere. In contrast, the hydrogen Hα and helium D_3 lines are emitted over a larger height range, extending well above the photosphere. The thin layer emitting the Mg I and Fe I/II lines can be used to identify the limb of the solar disk. Therefore the second contact can be considered to correspond to the disappearance of the magnesium and iron emission lines and the third contact to the reappearance of these lines. We observed the disappearance and the reappearance of these lines during the 1 August 2008 eclipse. According to the above consideration, the spectroscopically defined second contact occurred at 10:44:32 ± 1 s UT and the third contact at 10:46:33 ± 2 s UT, giving a duration of 2 m 01 s ± 2 s, centered at 10:45:32.5 ± 2 s UT. We note that the duration of the totality, defined by the Mg I and Fe I/II lines was shorter by 17.3 ± 2 seconds than the photospheric duration calculated by Espenak (Espenak and Anderson, 2007).

3. The 29 March 2006 Total Solar Eclipse at Kastellorizo, Greece

The observations of the total solar eclipse were undertaken at the patio of the Hotel Megisti ($\lambda = 29°35'28''.8$, $\varphi = +36°09'08''.6$) on the island of Kastellorizo. At that location the maximum of the eclipse occurred at 10:53:28.1 UT.

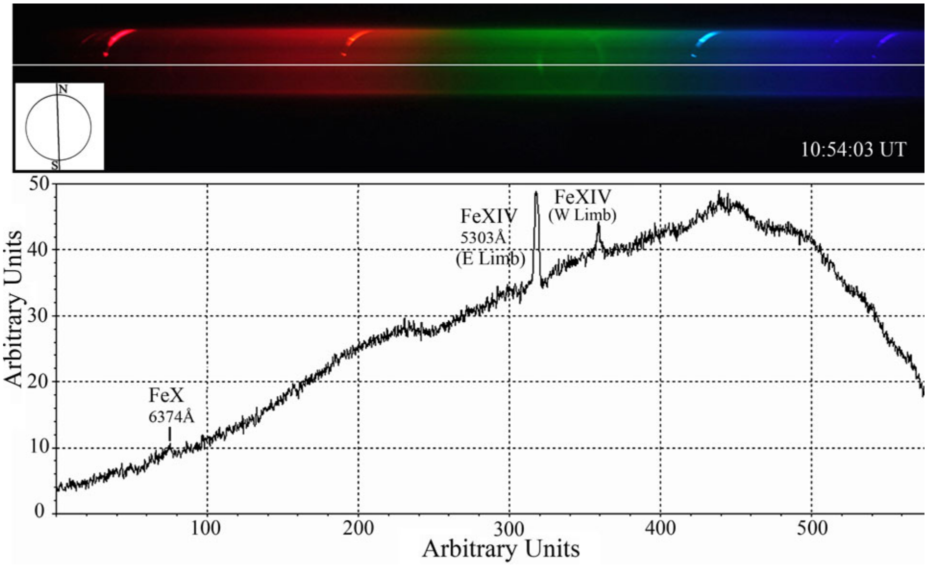


Figure 7 The flash spectrum of the 29 March 2006 total solar eclipse (top) and a cut through it (bottom). The cut in the bottom panel was taken along the white line in the top panel. The Fe XIV emission line is much stronger than the Fe X emission line.

3.1. The Slitless Spectrograph used during the 2006 Eclipse

A holographic transmission grating, with 566 lines/mm, used with an f/3.5 135 mm telephoto lens, was used for the recording of the flash spectrum during the total solar eclipse of 29 March 2006 at Kastellorizo. The system's efficiency was about 3% at 5303 Å (Fe XIV emission line) and 2% at 6374 Å (Fe X emission line). The lower efficiency of this system does not affect the results but the exposure time had to be increased to $\sim$1 second. We also used a digital Canon EOS 350D camera. The full range of the visible spectrum, from 3950 Å to 6700 Å, was projected on the CCD sensor of the digital camera. The resolution of the spectrograph was 0.9 Å/pixel. The diameter of the Sun corresponded to 285 pixels or $6.53''$/pixel. Spectra were recorded only during ingress. No data were recorded during egress.

3.2. The Flash Spectrum of the Total Solar Eclipse of 29 March 2006

The flash spectrum of the total solar eclipse of 29 March 2006 was recorded a few seconds before totality (Figure 7). Four CCD images were recorded, showing bright emission lines corresponding to chromospheric H and He. The Fe XIV green line, at 5303 Å was clearly visible, whereas the emission of the Fe X red line was almost absent.

4. Comparison of the 2006 and 2008 Flash Spectra

The Fe X and Fe XIV lines show obvious changes between the 2006 and 2008 eclipses. In particular the Fe X red line was much stronger in the 2008 spectra, whereas the Fe XIV green line was much stronger in the 2006 spectra (Figure 8). On the other hand, the chromospheric Hα and Hβ lines on the same spectra in Figure 8 are reasonably similar, which indicates that the above-mentioned differences in the Fe emission lines were genuine.

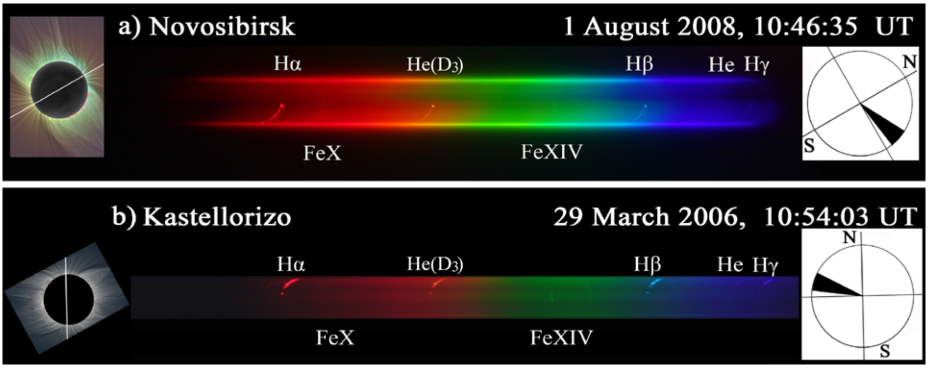


Figure 8 The solar spectra of the 1 August 2008 eclipse (top) and the 29 March 2006 eclipse (bottom). For each eclipse, the Sun's rotation axis is depicted as a white line in the left inset across one of our images. The wedge on the right inset depicts the heliographic latitude between 8° and 28°, where the observations were made (see text).

5. Measurements and Analysis

Initially, the original raw data were converted to FITS data, using the *IRIS* program (Buil, 2008). In order to be consistent, the calculations that follow were made at the same solar latitude for both the 2006 and the 2008 data. The orientation of the rotation axis of the Sun (see Figure 8, white lines) was estimated using the Observatoire de Paris – Meudon (2010), *Bass 2000 Solar Survey Archive*, grid lines and spectroheliographic images. The alignment was achieved by overlaying the *Bass 2000* (2010) grid images on our spectra, using the prominences that were present at the time of the eclipse. However, either because the diffractive efficiency of the ruled gratings decreases with increasing deviation from their principal direction or because the intensity of the Fe XIV emission declines with distance from the solar equator, the useful range was limited between heliographic latitude 8°N and 28°N (±0.3°). No active regions were present in this range or its vicinity, in both 2006 and 2008 eclipses. Within this range, the integrated intensity over the emission line profile of Fe X and Fe XIV in the images was calculated as well as above the continuum background. This was done for the east limb for the 2006 eclipse and for the west limb for the 2008 eclipse.

After the alignment of the spectra, the relative intensity, I_{Fe}, was calculated according to the formula

$$I_{\mathrm{Fe}} = (I_\lambda - I_{\mathrm{c}})/I_{\mathrm{c}},$$

where I_λ is the integrated intensity of each forbidden Fe coronal line and I_{c} is the corresponding intensity of the continuum background.

For the 2006 eclipse, the relative intensity for the Fe XIV line was $I_{\mathrm{Fe\,XIV}} = 0.039 \pm 0.001$ whereas for the Fe X line was $I_{\mathrm{Fe\,X}} = 0.022 \pm 0.001$. Therefore, the ratio of the relative intensities was

$$I_{\mathrm{Fe\,X}}/I_{\mathrm{Fe\,XIV}} = 0.58 \pm 0.01.$$

This ratio shows that the emission line of Fe XIV was much brighter than the corresponding Fe X line during the 2006 total solar eclipse at Kastellorizo.

For the 2008 eclipse, the relative intensity for the Fe XIV line was $I_{\mathrm{Fe\,XIV}} = 0.024 \pm 0.001$, whereas for the Fe X line was $I_{\mathrm{Fe\,X}} = 0.053 \pm 0.001$. Therefore, the ratio of the relative

Table 1 The relative intensities of the ionized iron lines for the 2006 and 2008 eclipses

Emission lines	2006, Kastellorizo Relative intensity	2008, Novosibirsk Relative intensity
Fe X	0.022	0.053
Fe XIV	0.039	0.024
Fe X/Fe XIV	0.58	2.16

intensities was

$$I_{\mathrm{Fe\,X}}/I_{\mathrm{Fe\,XIV}} = 2.16 \pm 0.05$$

This ratio shows that the emission line of Fe XIV was much weaker than the corresponding Fe X line during the 2008 total solar eclipse at Novosibirsk (Table 1).

Finally, we compare the ratio of the intensities of the Fe X and Fe XIV emission lines for the above eclipses. The results are presented in Table 2, where it becomes obvious that the relative intensity of Fe X to Fe XIV in the solar corona has increased substantially between 2006 and 2008.

6. Conclusions

As shown in Table 2, during the 2008 eclipse observed from Novosibirsk, the Fe XIV emission was much weaker than the Fe X emission. In contrast, during the 2006 eclipse observed from Kastellorizo, it was stronger. It should be noted that in the 1999 eclipse data, presented by Buil (2008), the Fe XIV line was also much stronger. Such changes could be attributed to the specific locations, where the data were taken in each observation. However, the continuous decline of the Fe XIV line intensity between 1999 and 2008 could be attributed to the decline of solar activity between 1999 and 2008. Solar activity was at a prolonged minimum during the 2008 eclipse, with sunspot number 0, whereas the sunspot number was about 20 during the period of the 2006 eclipse (still not high but certainly higher than 0) and 75 during the period of the 1999 eclipse. According to Esser *et al.* (1995), the intensities of the multiply ionized iron lines depend on the temperature of the corona (see their Figure 1b), so we are tempted to suppose that the decline of the Fe XIV emission was due to the decline of the corona temperature during the last two years (2006 – 2008). This, in turn, could be attributed to the very long and overdue minimum of the solar activity, which was reflected by the 345 (out of 856) spotless days between the 2006 and the 2008 total solar eclipses.

According to Nikolskaia and Utrobin (1984) the low intensity of the Fe XIV emission indicates that the temperature of the observed area must be less than 1.9×10^6 K. Similarly, the intensity of the Fe X emission line requires a corona temperature larger than 1.2×10^6 K. It is noted that the decrease of the Fe XIV emission line, could be attributed to either an increase or a decrease of the solar temperature. However, the absence of the high temperature lines of Ni XV 6702 Å (2.3×10^6 K), Ca XIII 4086 Å (2.3×10^6 K) and Ca XV 5694 Å (3.8×10^6 K) justifies our assumption that the decrease is due to a lower corona temperature (and not a higher one) (Halas *et al.*, 1997), as is already obvious from the intensity of X-ray emission.

Esser et al. (1995 – see their Figure 1) used two independent models (Brickhouse, Esser, and Habbal, 1995; Mason, 1975), to calculate the temperature of the solar corona as a function of the ratio of the Fe XIV/Fe X line intensities. Using the Fe XIV/Fe X data presented in Table 1, and the graphs of the above-mentioned figure, the temperature of the regions

Table 2 Ratio of the relative intensities of the Fe X and Fe XIV lines between 2006 and 2008

Fe X (Novosibirsk)/Fe X (Kastellorizo)	2.38
Fe XIV (Novosibirsk)/Fe XIV (Kastellorizo)	0.63

of the solar corona that we analyzed can be estimated: According to the model due to Brickhouse, Esser, and Habbal (1995), the drop of the temperature between 2006 and 2008 was $(1.1 \pm 0.1) \times 10^5$ K. According to the model of Mason (1975), it was a little larger, $(1.3 \pm 0.1) \times 10^5$ K. Mazzotta *et al.* (1998) present newer calculations of the ionization equilibrium for Fe X and for Fe XIV. Comparing our Fe X/Fe XIV estimates with the data presented in their Table 2, the drop of the temperature of the solar corona between 2006 and 2008 was $(3.0 \pm 0.5) \times 10^5$ K. Similar calculations of the relation of the ionic stage to temperature were carried out by J. Raymond (quoted in Golub and Pasachoff, 2009).

Habbal *et al.* (2010) discuss the inference of electron temperature from emission lines, and the change of emission from collisional to radiative domination. Our observations were in the inner, collisional region. Habbal *et al.* (2010) and also Habbal *et al.* (2009) and Daw *et al.* (2010) provide 2006 and 2008 eclipse observations of the Fe XI infrared line at 7892 Å. The latter paper provides a two-dimensional spatial comparison of the Fe XI specified as being similar to Fe X, Fe XIII, Fe XIV regions of prime emission, extending much higher in the corona than the regions shown in our spectra.

As discussed above, we attribute the drop of the temperature to the observed prolonged minimum of solar activity.

The duration of the flash spectrum was spectroscopically estimated from the appearance of the Hα emission line, which was observed during the ingress and during the egress phases of the 2008 eclipse.

Finally the disappearance and later reappearance of the neutral magnesium “b lines” (5167.3 Å, 5172.7 Å, 5183.6 Å) and the neutral (5168.9 Å) and the once-ionized iron (5169.1 Å) emission lines of the thin lower chromosphere were used to spectroscopically define the second and third contacts, respectively.

Acknowledgements We acknowledge the hospitality and assistance in Akademgorodok of Professor Alphya Nesterenko of the State University of Nobosibirsk and Dr. Igor Nesterenko of the Budker Institute of Nuclear Physics of the Russian Academy of Sciences. We also acknowledge the collaboration and assistance of Dr. Bryce A. Babcock throughout our observations at Kastellorizo and Akademgorodok. We are grateful for the assistance of John Antoniadis in the analysis used in Figure 6 and Professor Evaggelos Vanidhis of the Aristotle University in Thessaloniki, Greece, for help with the alignment of the optical instrumentation. We would also like to thank Marek Demianski, William G. Wagner, Eric Kutner, Jeffrey Kutner, Spyros Kanouras, George Pistikoudis and Kostas Tziotziou for logistical assistance. We benefited greatly from the comments of a referee. JMP and the Williams College Eclipse Expedition were funded by grants from the Heliospheric Division of the U.S. National Science Foundation and their Small Grants for Exploratory Research program, NASA, and the Committee for Research and Exploration of the National Geographic Society.

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