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COMPLEX VARIATIONS IN THE LINE-INTENSITY RATIO OF CORONAL EMISSION LINES WITH HEIGHT ABOVE THE LIMB

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ABSTRACT

We obtained spectroscopic observations simultaneously in pairs of coronal emission lines, one line being [Fe X] λ6374 and the other line being [Fe XI] λ7892, [Fe XIII] λ10747, or [Fe XIV] λ5303, and we studied the variations in the intensity and FWHM ratios of these lines with respect to those of 6374 Å as a function of height above the limb. We find that the intensity ratio of the 7892 and 10747 Å line with respect to the 6374 Å line increases with height and that the intensity ratio of 5303 Å to 6374 Å decreases with height above the limb. This implies that the temperature in coronal loops will appear to increase with height if we consider the intensity ratio of 7892 Å to 6374 Å a negligible variation in temperature in the case of the 10747 and 6374 Å line pair, while the temperature will appear to decrease with height if we consider the intensity ratio of 5303 Å to 6374 Å. The normalized FWHM (with respect to wavelength) ratio of 6374 Å to all the other coronal lines observed increases with height. The FWHM ratio at the limb depends on the pair of emission lines chosen; it is about 1 in the case of the 6374 and 7892 Å emission lines, indicating a common temperature and nonthermal velocity in the coronal loops near the limb, and it is about 0.7 at the limb in the case of the 6374 and 5303 Å lines and becomes about 1 at a height of 120″. The varying FWHM ratios with height indicate that hotter and colder plasmas in coronal loops mix with each other. Therefore, the observed increase in the FWHM of coronal emission lines, which are associated with plasma at about 1 MK with height, may not be due to an increase in nonthermal motions caused by coronal waves but may be due to an interaction with relatively hotter plasma.

Subject headings: Sun: corona — techniques: spectroscopic

1. INTRODUCTION

Temperature and nonthermal velocity variations in coronal loops may give us clues to the processes responsible for heating up the coronal plasma. While the intensity ratio of a suitable pair of coronal emission lines yields information about the temperature, the line widths of these lines indicate both the temperature and the nonthermal component of the coronal plasma. Studies of intensity ratios in order to determine the temperature and density variations in coronal loops are based mostly on EUV coronal lines using a filter ratio technique (Lenz et al. 1999; Aschwanden et al. 2000; Winebarger et al. 2003a). Earlier, following the discovery (Tousey et al. 1973; Vaiana et al. 1973) that the hot plasma is contained in closed magnetic structures, Landini & Monsignori Fossi (1975) and Rosner et al. (1978) recognized that the corona could be approximated as a set of one-dimensional loops that were thermally insulated from their surroundings. They solved the one-dimensional energy balance equation by assuming constant pressure, uniform heating, and a static, semicircular loop with a constant cross section, deriving two scaling laws that related the loop half-length and volumetric heating rate to the resulting apex temperature and base pressure. Serio et al. (1981) extended the scaling laws to allow for nonuniform pressure. Porter & Klimchuk (1995) found that the line-of-sight emission measures of the loops observed with the soft X-ray telescope on board *Yohkoh* were typically not equal to the emission measures derived from the scaling laws. Kano & Tsuneta (1996) found that the temperature and the emission measure are their highest at the loop top and that they decrease toward the footpoints. They also found that the correlation between the total energy loss and the gas pressure for the steady loops is consistent with the theoretical energy scaling law. Guhathakurta et al. (1993, 1996) studied the intensity ratio of the 5303 Å line to the 6374 Å line to derive the temperature and density of the solar corona. We also study the variation in the intensity ratio and the FWHM of these two and of other observed coronal emission lines to determine the variation in temperature with height above the limb.

2. OBSERVATIONS AND DATA ANALYSIS

We made spectroscopic observations simultaneously in pairs of coronal lines, [Fe X] λ6374 and [Fe XI] λ7892, [Fe XIII] λ10747, or [Fe XIV] λ5303, with the 25 cm coronagraph at the Norikura Observatory (Singh et al. 1999, 2003a, 2003b). We mounted two CCD cameras on the coudé spectrograph in order to make observations in two emission lines simultaneously. Here we mention the main features of the observations; the details may be seen in Singh et al. (1999). Off the limb, raster scans of a coronal region of about 200″ × 500″ size were obtained with a step size of 3″–5″ by keeping the slit parallel to the limb. An exposure time of 10–20 s permitted us to complete a raster scan in 10–30 minutes. The binned CCD pixels (2 × 2) provided us with a spatial resolution of 2″ and a spectral resolution of 58, 48, 121, and 32 mÅ pixel^{-1} at the 6374, 7892, 10747, and 5303 Å, respectively. Spectra of disk center were obtained with a neutral density filter mounted in front of the spectrograph slit immediately after the raster scan to determine the coronal intensities in absolute units. The transmission of the neutral density filter is 0.2609%, 0.3402%, 3.712%, and 3.532% at 6374, 7892, 10747, and 5303 Å, respectively, as measured using the scanning spectrophotometer UV-3100PC, Shimazu Corp., available at the National Astronomical Observatory of Japan. Dark and flat-field images were also obtained with the same experimental setup. These observations were

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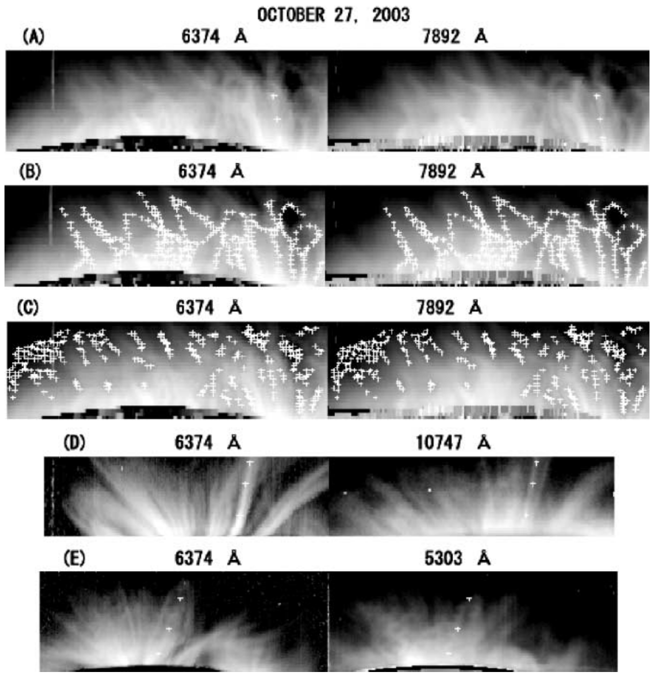

FIG. 1.—Panel A shows the intensity distribution of the 6374 and 7892 Å emission lines observed simultaneously in a coronal region of 200″ × 500″ size observed on 2003 October 27. The plus signs in panels B and C show the locations chosen to study the variations with height for coronal loops and diffused plasma in between the loops, respectively. Panel D shows the intensity distribution of the 6374 and 10747 Å lines, and panel E shows the instensity distribution of the 6374 and 5303 Å emission lines.

made on a number of days, and data on many coronal regions were obtained during 1997–2003.

First we subtracted the dark signal from the spectra, did flat-fielding, and then subtracted the photospheric scattered light component using the disk center spectra obtained just after the raster scan. The Gaussian fits were made to the line profiles to compute the peak intensity, line width, and Doppler velocity at each location of the observed coronal region. Figure 1 shows the intensity distribution in three coronal regions observed simultaneously in the 6374 and 7892 Å lines on 2003 October 27, in the 6374 and 10747 Å lines on 1998 September 10, and in the 6374 and 5303 Å lines on 1998 June 30. We chose 300 locations on the coronal loops that were visible in the 6374 Å line image displayed on the monitor, and the corresponding locations in the other line image were selected using the software. We computed the line intensity I_l from the Gaussian fit to the emission line using the following relation: $I_l = (I_p TF) \times \mathrm{FWHM}/(tN)$, where I_p is the peak intensity of the Gaussian fit, T is the transmission of the neutral density filter used to take the disk spectrum, F is the disk center flux at the wavelength of the emission line as given by Allen (1973, p. 179), FWHM is the full width at half-maximum intensity corrected for the instrumental effects, t is the exposure time for the coronal spectra in seconds, and N is the disk center intensity per second at the continuum close to the wavelength of the emission line. Plots of the intensity ratio and the FWHM as a function of height are shown in Figure 2. We did a similar analysis for the diffused plasma in between coronal loops and for the observations in other emission lines. It may be noted that the FWHM of the 6374 Å emission line increased with height in all coronal structures (Singh et al. 2003a, 2003b) except for two, one observed on 1998 September 19–20 and the other on 2003 October 27, where the FWHM of the 6374 Å line decreased with height.

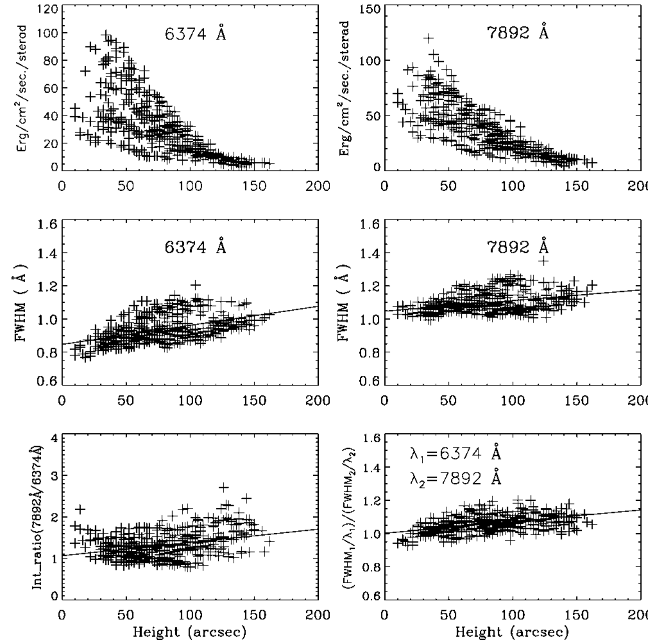

FIG. 2.—The left and right panels in the top row show the intensity in the 6374 and 7892 Å emission lines for the coronal loops as a function of height above the limb. The panels in the second row show the FWHM of these lines as a function of height. The left and right panels in the bottommost row show the intensity ratio of 7892 Å to 6374 Å and the FWHM ratio of 6374 Å to 7892 Å with height, respectively.

3. RESULTS AND DISCUSSIONS

Panel A of Figure 1 shows a typical example of intensity distribution in a coronal structure in 6374 and 7892 Å emission lines. The plus signs in panels B and C show the locations chosen for study in the loops and the diffuse plasma in between the loops, respectively. Panels D and E show the coronal regions observed in 6374 and 10747 Å and in 6374 and 5303 Å, respectively, on two other occasions. Figure 2 was generated from the data on locations shown in panel B of Figure 1. The two plots in the first row of Figure 2 show the absolute intensities of 6374 and 7892 Å emission lines as a function of height above the limb, while those in the second row show their FWHMs. The left panel in the third row shows the intensity ratio of 7892 Å to 6374 Å as a function of height. A linear fit to the data indicates that the ratio increases from a value of 1.05 at limb to a value of about 1.55 at 150″ above the limb. The ratio of the normalized FWHM with respect to the wavelength along with the linear fits to the data is shown in the right panel of the third row. The FWHM ratio increases from about 1 at limb to 1.12 at 150″ above the limb. The analysis of the data for diffuse plasma yields results similar to those for the coronal loops. The two top panels of Figure 3 indicate that the intensity ratio of 10747 Å to 6374 Å also increases with height in coronal loops, but by only 10% over a height of 150″. The FWHM ratio of 6374 Å to 10747 Å increases with height from a value of 0.78 at the limb to only 0.84 at 150″ above the limb. The other two panels in the bottom of Figure 3 show the results of simultaneous observations in the 6374 and 5303 Å lines where we find that the intensity ratio of 5303 Å to 6374 Å decreases from about 5 at the limb to 2.5 at 150″ above the limb, while the FWHM ratio

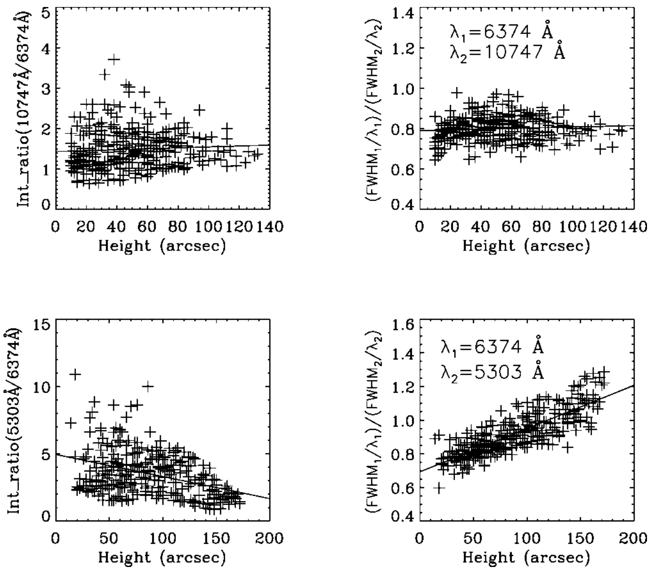

FIG. 3.—The two panels in the top row show the intensity ratio of 10747 Å to 6374 Å and the FWHM ratio of 6374 Å to 10747 Å (normalized to the wavelengths) as a function of height above the limb. The two panels in the bottom row show similar plots for the observations made simultaneously in the 6374 and 5303 Å lines.

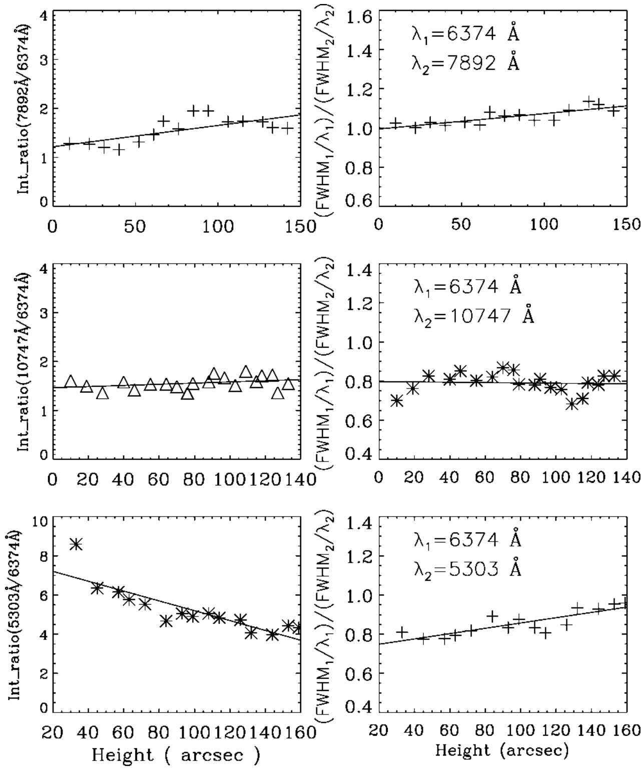

FIG. 4.—Variation of intensity and FWHM ratios with height for the individual coronal loops.

of 6374 Å to 5303 Å increases from 0.7 at the limb to 1.1 over the same height. The analysis of diffuse plasma in between coronal loops also yields results that are similar to those for the loops in these emission lines also. The plus signs in the panels A, D, and E of Figure 1 show the individual coronal loops chosen, and Figure 4 shows variations in the intensity and FWHM ratios as a function of height for these loops. A comparison of the loop chosen (panel D, Fig. 1) in the 6374 Å line and automatically picked up by the software in the 10747 Å line indicates that the plasma responsible for emitting these radiations coexists in the loop as shown earlier by Singh et al. (2003a). This is also true for the loop chosen in 6374 and 5303 Å as seen in panel E of Figure 1.

We made spectroscopic observations in the coronal lines on a large number of days. The magnitude of variations of FWHM and intensity ratios with height depends on the particular coronal structure observed, indicating that these parameters are sensitive to the underlying magnetic field configuration, density, temperature, and the state of evolution of a coronal structure. But the general trend in the variation with height for different emission lines remains the same; e.g., the intensity ratio 7892 Å/6374 Å and the FWHM of the 6374 Å line increase with height in about 90% of the coronal loops studied, and the intensity ratio of 5303 Å/6374 Å and the absolute value of the FWHM of the 5303 Å line decrease with height in almost all of the structures.

The intensity ratio 5303 Å/6374 Å is a strongly varying function of temperature, but a weakly varying function of density (Guhathakurta et al. 1993). T. Sakurai (2004, in preparation) finds a similar result for the 6374 and 7892 Å emission-line pair. Therefore, the increase in the intensity ratio of 7892 Å to 6374 Å with height above the limb indicates an increase in temperature with height in coronal loops. The inntensity ratio 10747 Å/6374 Å also shows a small increase with height. However, the intensity ratio of 5303 Å/6374 Å decreases with height, implying a decrease in temperature in coronal loops. A major fraction of the scatter observed in the intensity ratio 5303 Å/6374 Å arises from the fact that the variation in the ratio across a coronal loop is larger than that along the loop. The differences in the physical properties of coronal loops examined also contribute to the scatter, but to a lesser extent. The computed probable uncertainties in the intensity ratio at the limb and in the slope of linear fit are given in Table 1. The χ^2-values also listed in Table 1 indicate that the confidence level of the linear fits is very high. The uncertainties are much smaller in spite of visible large scatter in the plots of all loops considered together, probably because of the large database. The uncertainties in the case of the FWHM ratio are smaller or equal to those in the intensity ratio. The abundances of ions given by Arnaud & Raymond (1992) for a temperature range of 1–2 MK implies that a given increase in temperature with height in the loop will lead to a positive gradient in the intensity ratio 7892 Å/6374 Å, a larger gradient in 10747 Å/6374 Å, and a much larger gradient in 5303 Å/6374 Å. But our observations show a smaller gradient in the 10747 Å/6374 Å intensity ratio and a decrease in the 5303 Å/6374 Å intensity ratio when compared to the 7892 Å/6374 Å intensity ratio. The increase in the intensity ratio 7892 Å/6374 Å from about 1.1 at limb to 1.55 at 150″ height implies an increase in temperature of 0.15 MK (T. Sakurai 2004, in preparation). It may be noted that the intensity ratio of two emission lines indicates a small variation in temperature with height, whereas the FWHMs of the respective lines imply a large variation in temperature or nonthermal velocity. Therefore, it appears that the temperature as well as the nonthermal velocity vary with height above the limb in steady coronal structures.

The solutions of the hydrodynamic equations for the coronal loops predict a steep temperature rise from the loop footpoint through the transition region and a small, but measurable, temperature increase from the top of the transition region to the loop apex (Winebarger et al. 2003b). Our simultaneous obser-

TABLE 1
Intensity Ratio at Limb, Gradient of Intensity Ratio with Height, Probable Uncertainties, and Values of χ^2

Line Pairs	Intensity Ratio at Limb	Intensity Ratio Slope	χ^2
For All Loops			
6374 and 7892 Å	1.06 ± 0.04	0.003 ± 0.0004	1.00
6374 and 10747 Å	1.43 ± 0.06	0.001 ± 0.001	0.98
6374 and 5303 Å	4.95 ± 0.23	−0.016 ± 0.002	0.99
For Individual Loops			
6374 and 7892 Å	1.21 ± 0.06	0.004 ± 0.0005	0.98
6374 and 10747 Å	1.46 ± 0.07	0.001 ± 0.0007	0.98
6374 and 5303 Å	7.71 ± 0.45	−0.025 ± 0.004	0.99

vations in the 6374 and 7892 Å lines agree with this scenario, but the observations in the 6374 and 5303 Å lines do not. The negligible increase in the intensity ratio 10747 Å/6374 Å with height is similar to that reported by Lenz et al. (1999) because they used [Fe IX] and [Fe XII] lines for their study and because the temperature of maximum ion abundance differs slightly for [Fe XII] and [Fe XIII] (present study). Our observations in these four emission lines show that the increase or decrease of the intensity ratio along a coronal loop depends on the line pairs selected for such a study. Simultaneous observations in the 10747 and 5303 Å lines will be a better choice to investigate the variation of temperature with height in relatively hotter coronal loops because of the small difference in the temperature of the maximum ion abundance of the lines.

A comparison of Figure 4 with Figures 2 and 3 indicates that individual coronal loops show similar variations in intensity and FWHM ratios with height as those found while considering all the loops together. This implies that all types of loops show similar variations and thus indicates that observed variations in the intensity and FWHM ratios with height may not be due to a population of different types of loops. In addition, the values of the FWHM and the gradients of the FWHM and the intensity ratio are almost the same for coronal loops and diffuse plasma. The observed variation in the intensity and FWHM ratios cannot be explained by the monotonic increase/decrease in temperature or nonthermal velocity, the type of loop, or the integration along the line of sight (Singh et al. 2003a, 2003b). The decrease in temperature with height of the relatively hotter plasma, the increase in temperature with height of the relatively colder plasma, the common (thermal+nonthermal) velocity for relatively colder plasma due to two different ion spices contributing to emission at 6374 and 7892 Å near the limb, and the common (thermal+nonthermal) velocity for hot (5303 Å) and cold (6374 Å) plasma at larger heights in the corona indicate the mixing of hotter and colder plasma in coronal loops. The mixing of plasma may mean that the hotter plasma gives part of its energy to the colder plasma, probably because of a collisional process. The mixing or diffusion of plasma between loops represented by different temperatures increases with height along the coronal loops, probably because of an increase in the ratio of gas pressure to magnetic pressure with height above the limb. The mixing results in plasma emitting 6374 Å radiations at larger heights that are hotter than the plasma at lower heights and in plasma emitting 5303 Å radiations at larger heights that are cooler than plasma at lower heights and thus explains the observed variations in the intensity and FWHM ratios of different coronal emission lines.

These findings suggest the need to incorporate the mixing of plasma of different temperatures in the model of coronal loops, since the assumption of a static loop containing a single-temperature plasma is grossly inadequate. Since these findings have far-reaching implications, especially with regard to the coronal heating, further confirmation is needed based on simultaneous observations in these four lines and EUV emission lines sensitive to the temperature range of 1–2 MK with high spectral resolution.

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