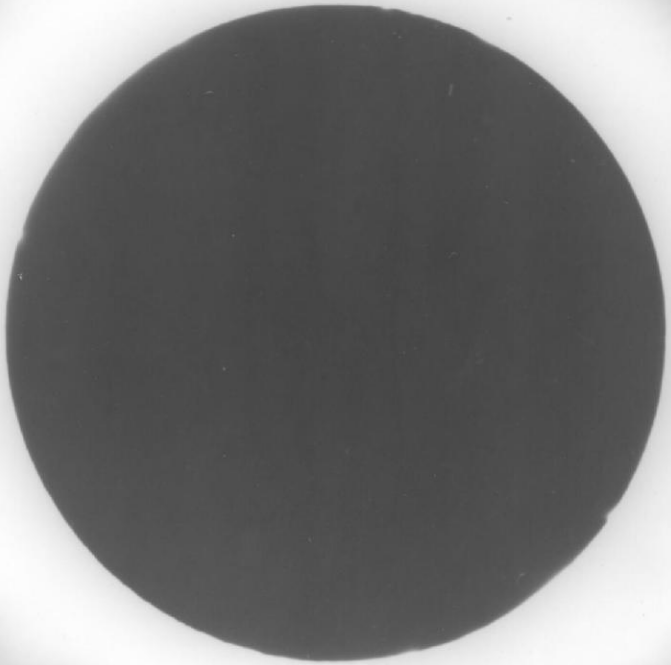
Emission line spectroscopy of the solar corona and implications to coronal heating



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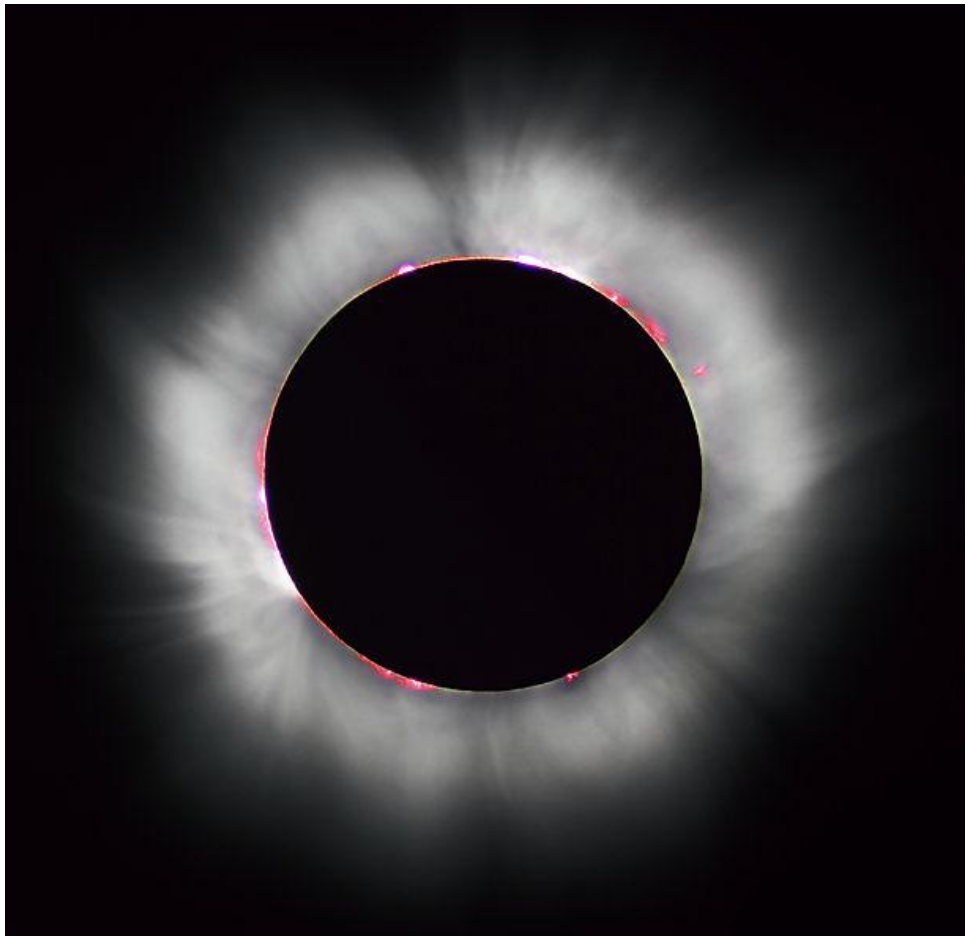
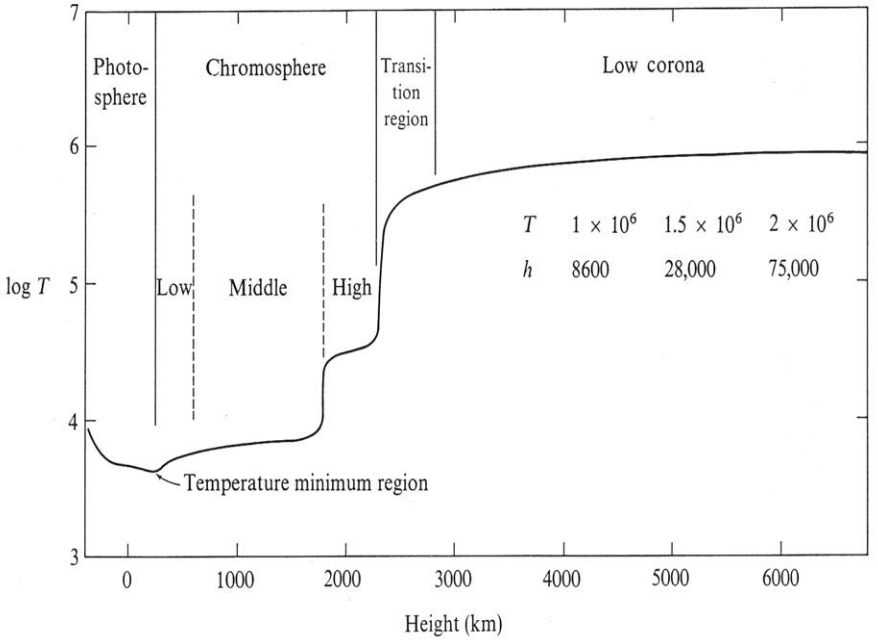
Solar Corona

- A low density plasma outside the visible disk of the Sun (10^{-12} of the photospheric density).
- High temperature (a factor of 200 compared to the photosphere).
- Emission in EUV and X-rays are higher compared to the photosphere.
- Low intensity in the visible wavelength (10^{-6} times of the photosphere).
- Corona is separated from the photosphere by Chromosphere.



Coronal Temperature

- Million Degree – Observed from the line less scattered light by electrons as well as the emission from highly ionized species.
- Edlen 1939 – Coronal Green Line.
- Why so high temperature is yet to be solved?



Heating of Coronal Plasma

- Existence of waves in the corona: Nature of waves, MHD waves, Fast magneto- sonic waves, dissipation of waves
- Large scale reconnections: Flares, eruptive prominences, CME's etc
- Small scale reconnections: Micro flares, Nano flares
- Modeling of solar corona: Energy budget

Heating of solar coronal plasma is still not clear?

If the systematic spectroscopic observations of the solar corona support any of the above mentioned process or processes to heat up the plasma in the corona?

Coronal loops

- Generally the coronal loops are considered to be isothermal in nature.
- The magnetic pressure is believed to be high as compared to the gas pressure in the coronal loops
- The loops are thin and are magnetically shielded from other temperature loops
- Mostly increase in line-width of coronal emission lines with height has been interpreted in terms of increase in non-thermal velocities with height due to coronal waves
- Do systematic observations of coronal emission lines confirms these?

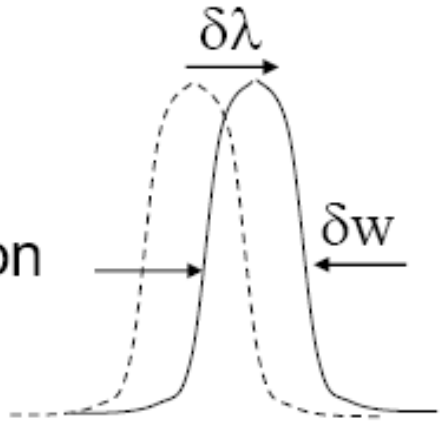
Observables

Information from a single emission line

Line intensity

Line shift by Doppler motion

Line width: temperature, non-thermal motion



Information from selected two line ratio

Temperature

Density

Spectroscopic observations:

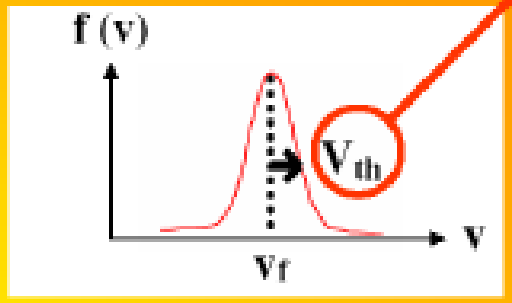
The line width : a mix of 2 informations

Gaussian width : (optically thin)

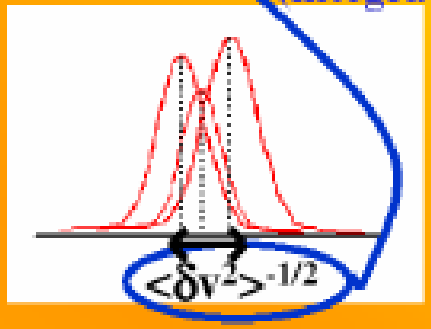
$$\sigma^2 = \frac{\lambda^2}{2c^2}\left(\frac{2kT}{M} + \xi^2\right) + \sigma_I^2.$$

Instrumental width

Thermal Doppler effect (one volume element) :



« non-thermal » velocity (integration effect)



- **Temperature** : thermal Doppler effect in one volume element
- « **non-thermal velocity** », or « unresolved velocity » : results from the integration over a lot of volume elements driven by fluid velocity fluctuations :
  - → on the line of sight
  - → on spatial and temporal scales smaller than the resolution scale

Source of velocity fluctuations : Alfvén waves, turbulence ?

Emission line-width

- FWHM of coronal emission lines has two components
- Thermal component which arises because of high temperature of the plasma in the solar corona
- Non-thermal component- The observed line width of the coronal emission lines was found to be in excess of thermal broadening. e. g. The observed width of the green line [Fe xiv] at 5303 A coronal emission line corresponds to a temperature between 3 – 4 MK where as maximum abundances of this ion occurs at about 2 MK
- The excess width has been interpreted in terms of non-thermal component, probably due to turbulence.

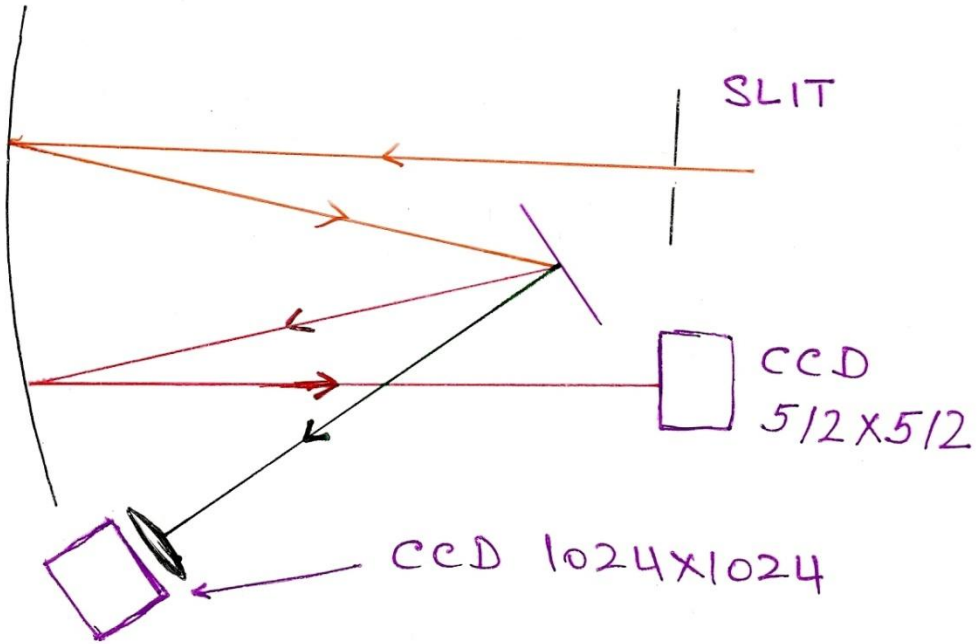
Table 8.3. Important forbidden coronal lines in the visible (Jefferies *et al.* 1971).

λ(Å)	Transition	A_{21} (sec^{-1})	Excit. Pot.	Ioniz. Pot.	Int*
3328	CaXII $2p^5\ ^2P_{1/2} \rightarrow\ ^2P_{3/2}$	488	3.72	589	(17)
3388	FeXIII $3p^2\ ^1D_2 \rightarrow\ ^3P_2$	87	5.96	325	37
3601	NiXVI $3p\ ^2P_{3/2} \rightarrow\ ^2P_{1/2}$	193	3.44	455	(18)
3642.9	NiXIII $3p^4\ ^1D_2 \rightarrow\ ^3P_1$	18	5.82	350	1.5
3986.9	FeXI $3p^4\ ^1D_2 \rightarrow\ ^3P_1$	9.5	4.68	261	
4086.3	CaXIII $2p^4\ ^3P_1 \rightarrow\ ^3P_2$	319	3.03	655	(22)
4231.4	NiXII $3p^5\ ^2P_{1/2} \rightarrow\ ^2P_{3/2}$	23	2.93	318	8
4412	ArXIV $2p\ ^2P_{3/2} \rightarrow\ ^2P_{1/2}$	112	2.84	682	16
5116.03	NiXIII $3p^4\ ^3P_1 \rightarrow\ ^3P_2$	157	2.42	350	2
5302.86	FeXIV $3p\ ^2P_{3/2} \rightarrow\ ^2P_{1/2}$	60	2.34	355	190
5445	CaXV $2p^2\ ^3P_2 \rightarrow\ ^3P_1$	83	4.45	814	(15)
5539	ArX $2p^5\ ^2P_{1/2} \rightarrow\ ^2P_{3/2}$	106	2.24	421	5
5694.42	CaXV $2p^2\ ^3P_1 \rightarrow\ ^3P_0$	95	2.18	814	(28)
6374.51	FeX $3p^5\ ^2P_{1/2} \rightarrow\ ^2P_{3/2}$	69	1.94	233	40
6701.83	NiXV $3p^2\ ^3P_1 \rightarrow\ ^3P_0$	57	1.85	422	(27)
7059.62	FeXV $3s3p\ ^3P_2 \rightarrow\ ^3P_1$	38	31.77	390	5
7891.94	FeXI $3p^4\ ^3P_1 \rightarrow\ ^3P_1$	44	1.57	261	50
8024.21	NiXV $3p^2\ ^3P_2 \rightarrow\ ^3P_1$	22	3.39	422	
10746.80	FeXIII $3p^2\ ^3P_1 \rightarrow\ ^3P_0$	14	1.15	324	100
10797.95	FeXIII $3p^2\ ^3P_2 \rightarrow\ ^3P_1$	9.7	2.30	325	50

Plasma Temperatures

- 6374 [Fe x] line represents plasma at ~1 MK
- 7892 [Fe xi] line represents plasma at ~1.2 MK
- 10747 [Fe xiii] line represents plasma at ~1.6 MK
- 5303 [Fe xiv] line represents plasma at ~1.8 MK

It does not mean that these lines do not show any emission at other temperatures



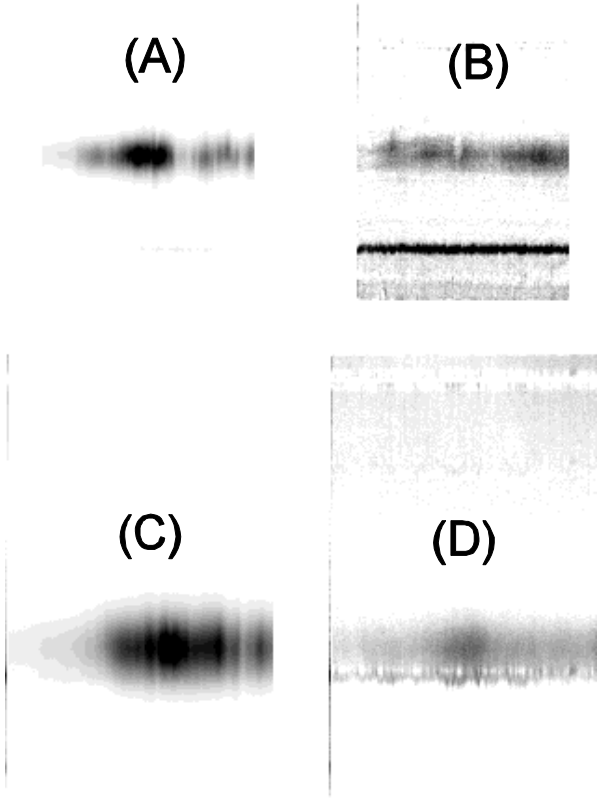
Possible combination of emission lines
for observations

S. No.	Littrow focus (Order)	Second focus (Order)
1.	6374 A (III)	5303 A (IV)
2.	6374 A (III)	10747 A (II)
		10798 A (II)
3.	7892 A (III)	6374 A (IV)
4.	6374 A (IV)	7892 A (III)

Observations

- Systematic observations of 4 coronal emission lines in the visible wavelengths with 25 cm coronagraph of Norikura observatory from 1997 to 2007
- Choosing two emission lines simultaneously; 6374 [Fe x] & 7892 [Fe xi] or 6374 [Fe x] & 5303 [Fe xiv] or 6374 [Fe x] & 10747 [Fe xiii]
- Most of the raster scan covered coronal region of about 500 x 200 arc sec. Some covered coronal region of 500 x 500 arc sec.
- Error estimate in FWHM measurements are about 2 mA near the limb and about 5 mA at 500 arc sec height
- Recently we have obtained observations in 4 emission lines simultaneously; 7892, 10747, 10798 and 5303 lines

Scattered light corrected spectra in the red and green emission lines at 50 arcsec (C & D) and at 300 arcsec above the solar limb (A & B)



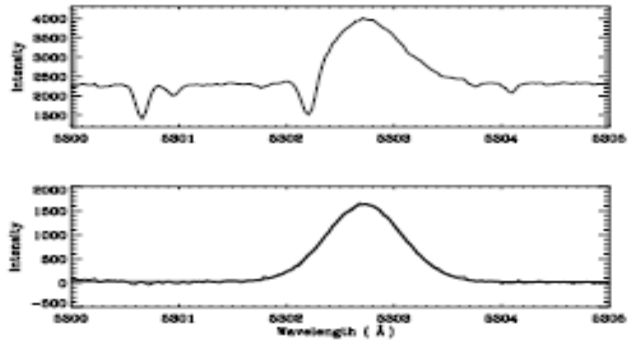


FIG. 1*a*

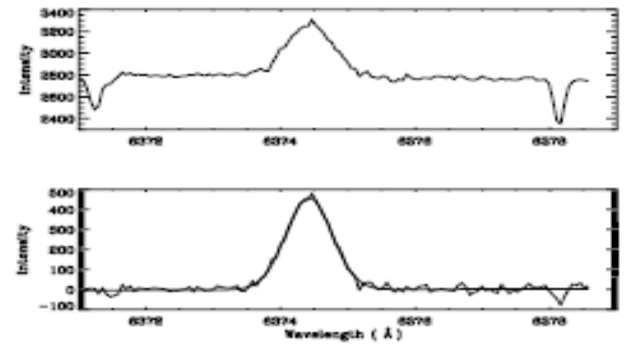


FIG. 1*b*

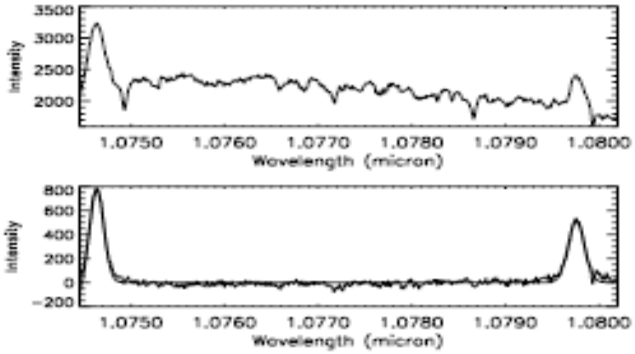
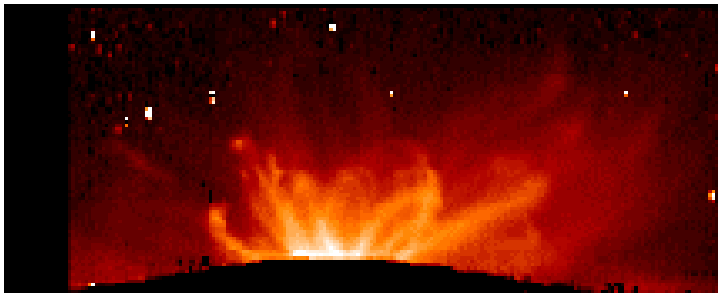


FIG. 1*c*

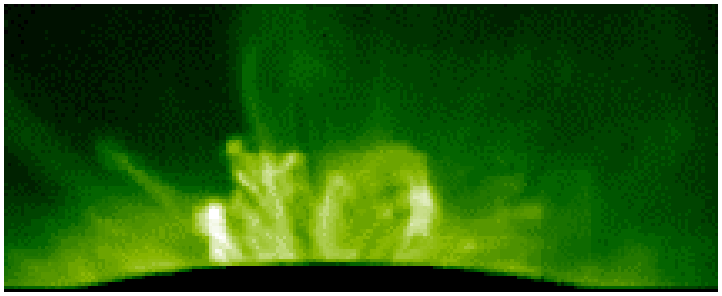
FIG. 1.—(*a*) Top panel shows a typical observed profile for the green coronal emission line (5303 A). The residual profile after corrections for the dark frame, flat field, and scattered light due to sky brightness, and a Gaussian fit to the profile are shown in the bottom panel. (*b*) Same as (*a*), but for the red coronal emission line (6374 A). (*c*) Same as (*a*), but for the two infrared emission lines at 10747 and 10798 A.

Observed and corrected profiles of green, red and infra-red coronal emission lines

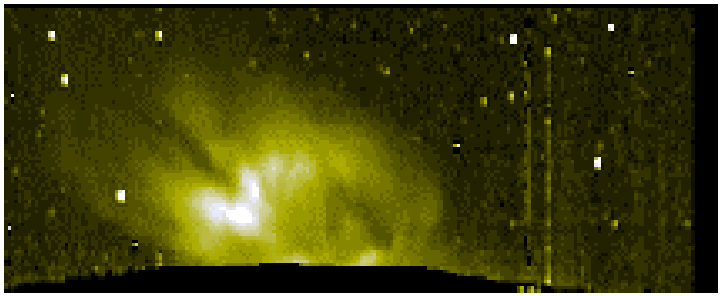
FeX 6374A (1MK)



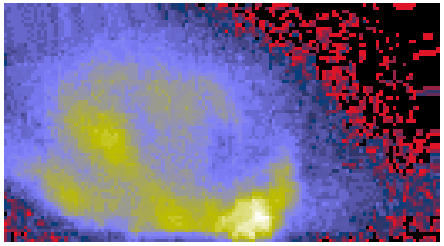
FeXIV 5303A (2MK)



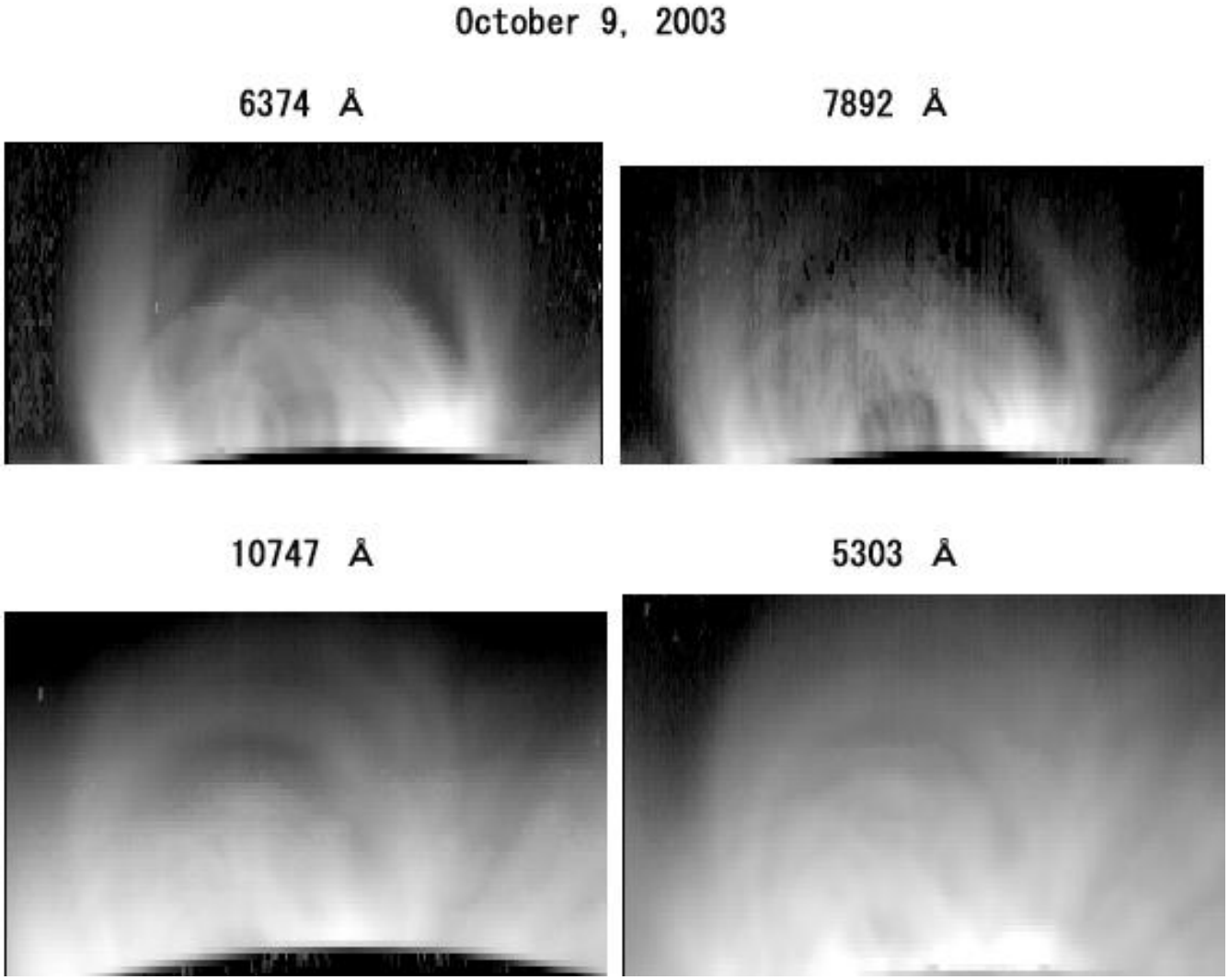
CaXV 5694A (3.5MK)



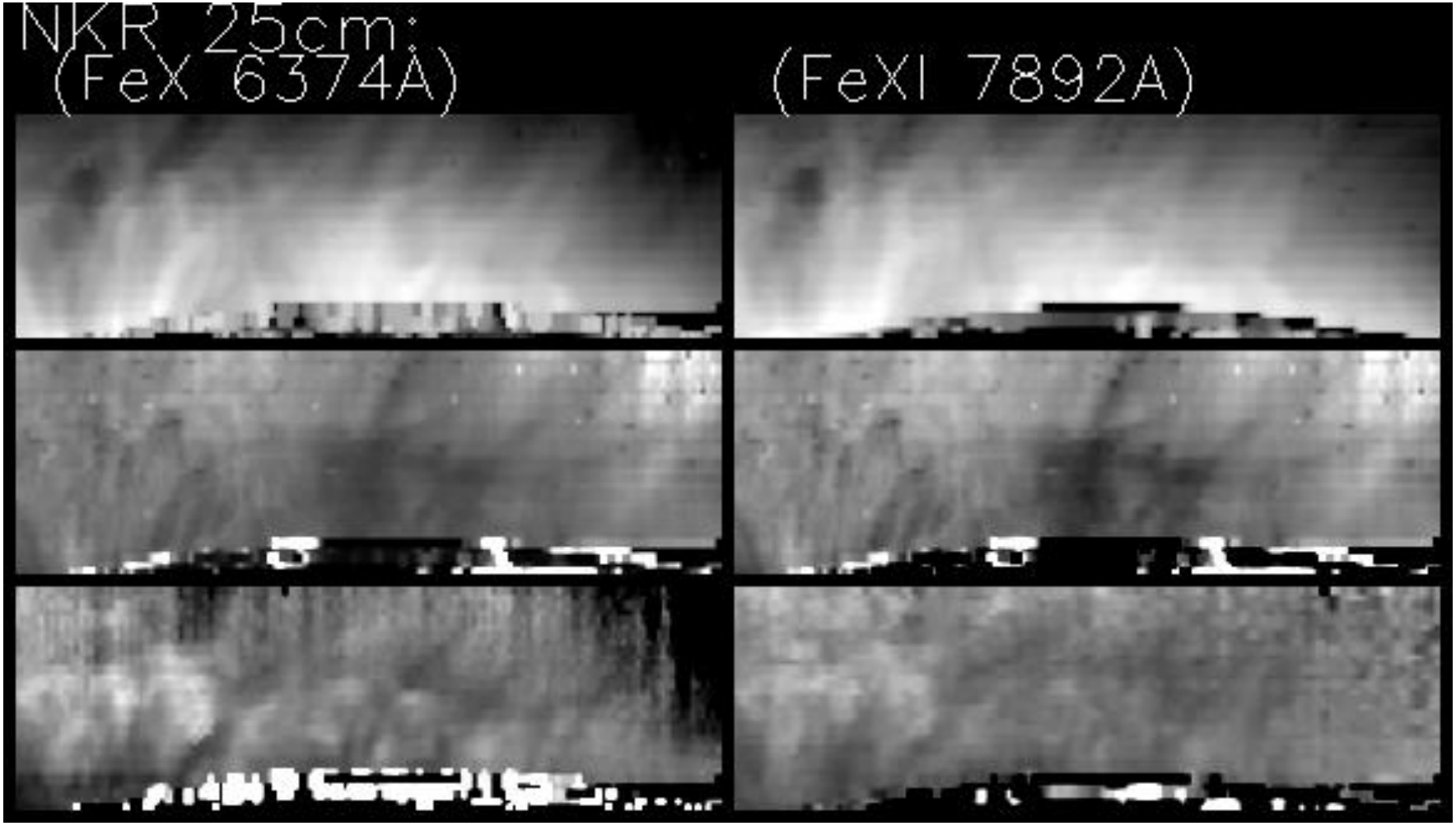
Yohkoh SXT /Al1.1
(3—6MK?)



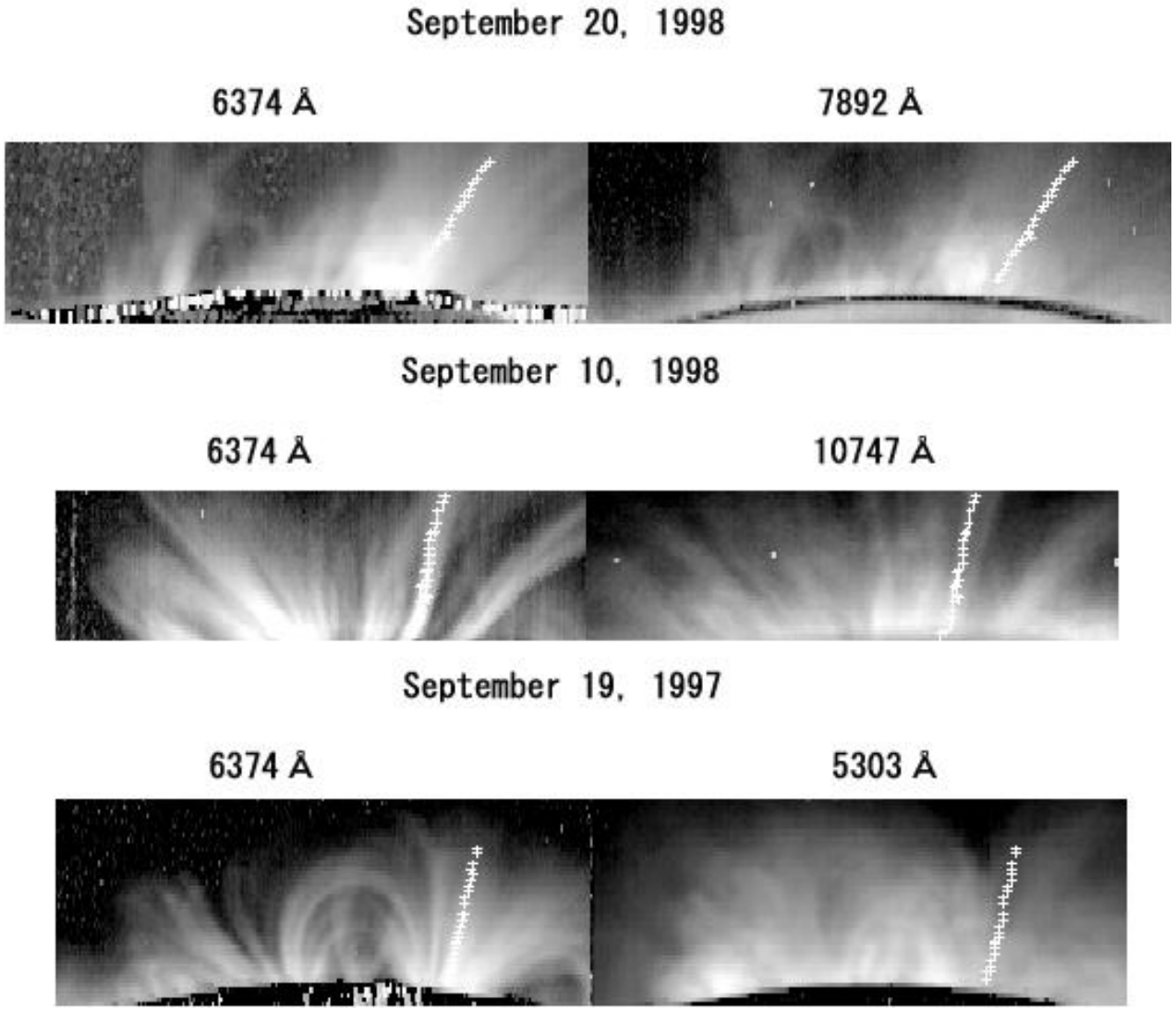
A coronal region observed in [Fe x], [Fe xi], [Fe xiii] and [Fe xiv] lines but not simultaneously



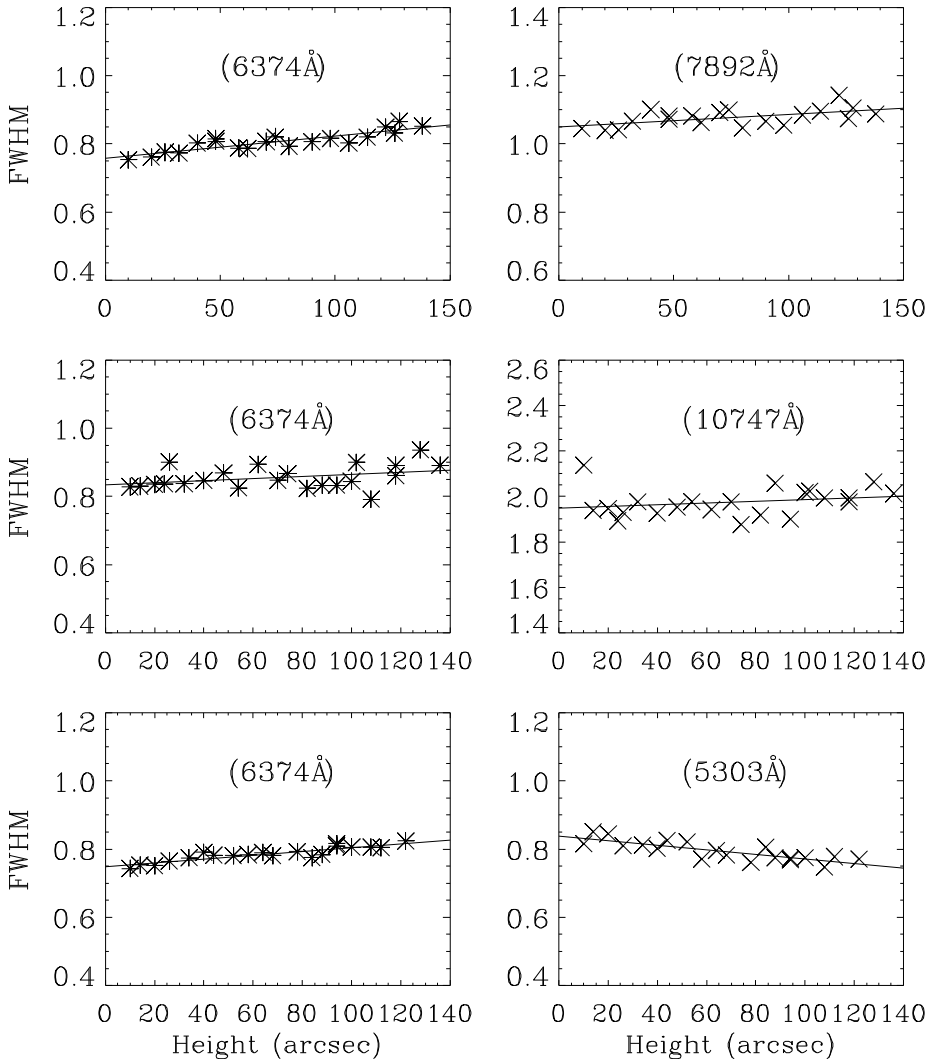
Distribution of intensity, line-of-sight velocity and line-width in a coronal region observed on Oct 27, 2003 simultaneously in [Fe x] and [Fe xi] coronal emission lines

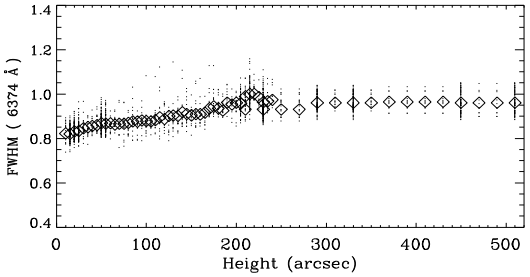


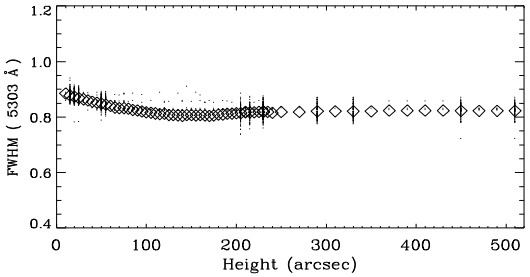
Three typical coronal loops selected by + marks to study the variation of line-widths with height above the limb

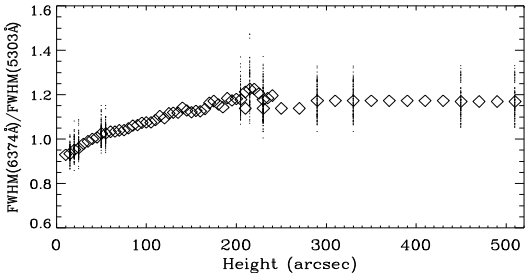


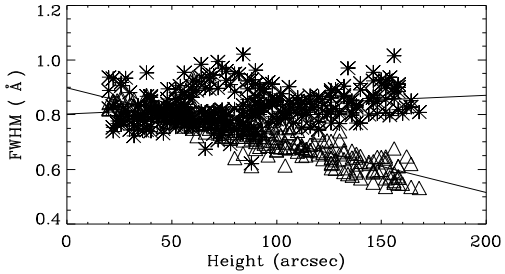
Typical variation of line width of emission lines with height for individual coronal loop

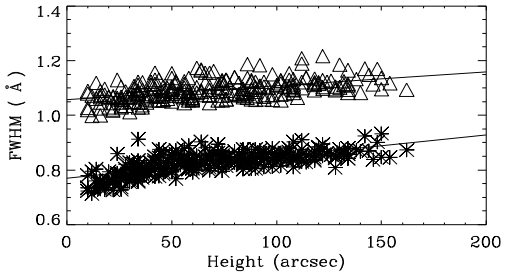


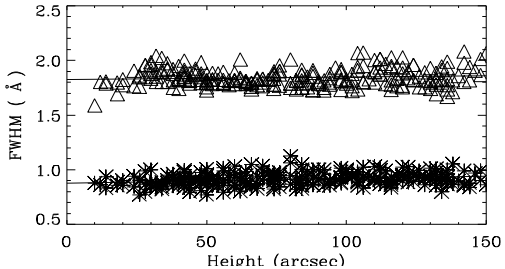

FWHM (6374 Å)
Height (arcsec)

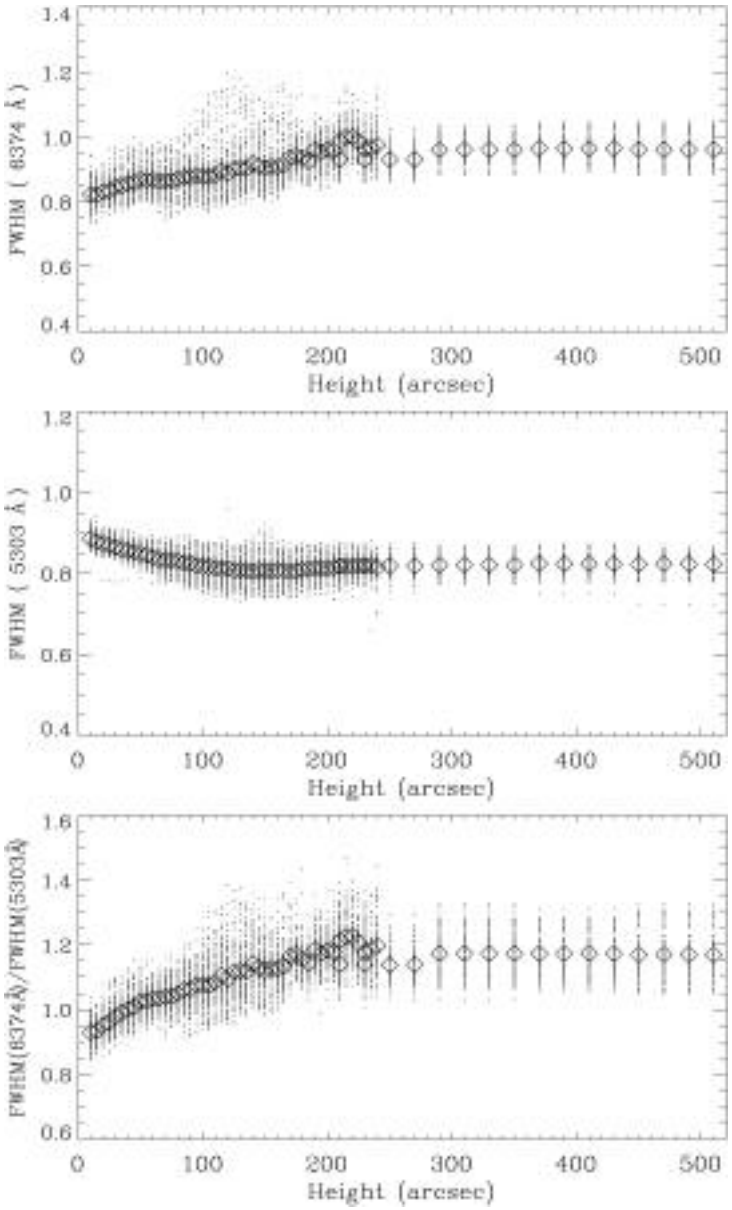

FWHM (5303 Å)
Height (arcsec)


FWHM(6374Å)/FWHM(5303Å)
Height (arcsec)


FWHM (Å)
Height (arcsec)

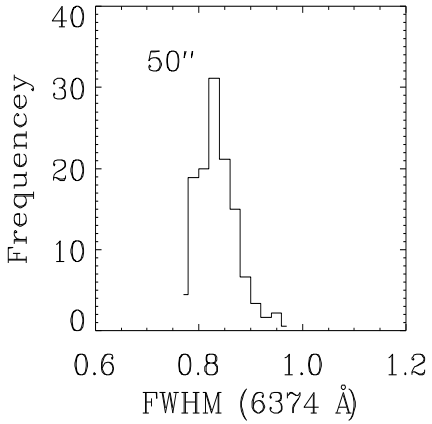

FWHM (Å)
Height (arcsec)

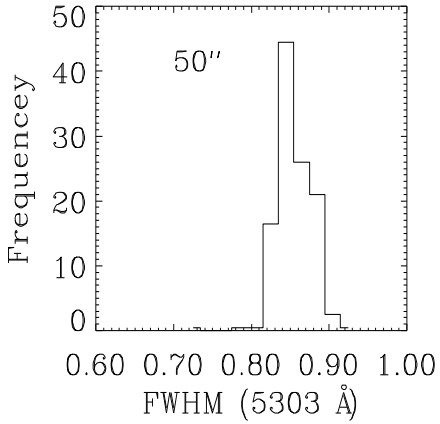

FWHM (Å)
Height (arcsec)

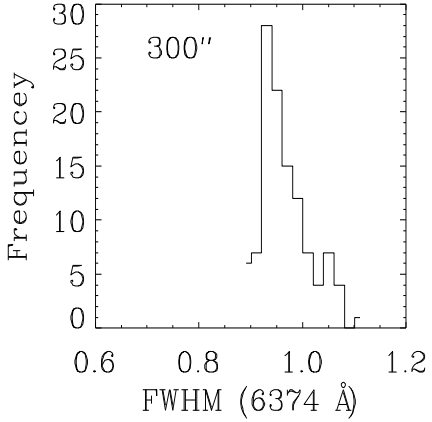


Variation of line widths of red and green coronal emission lines with height above the limb up to 500 arcsec. The line widths do not show any increase or decrease with height after about 250 arcsec

Frequency distribution of line widths of red and green emission lines at 50 and 300 arcsec







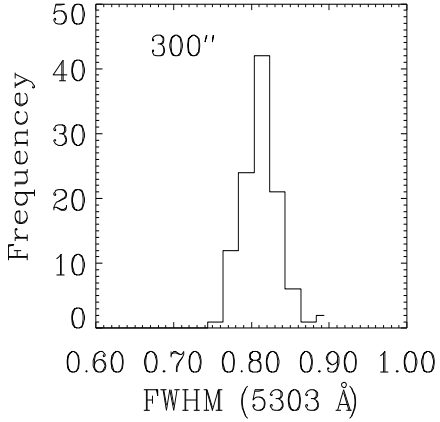
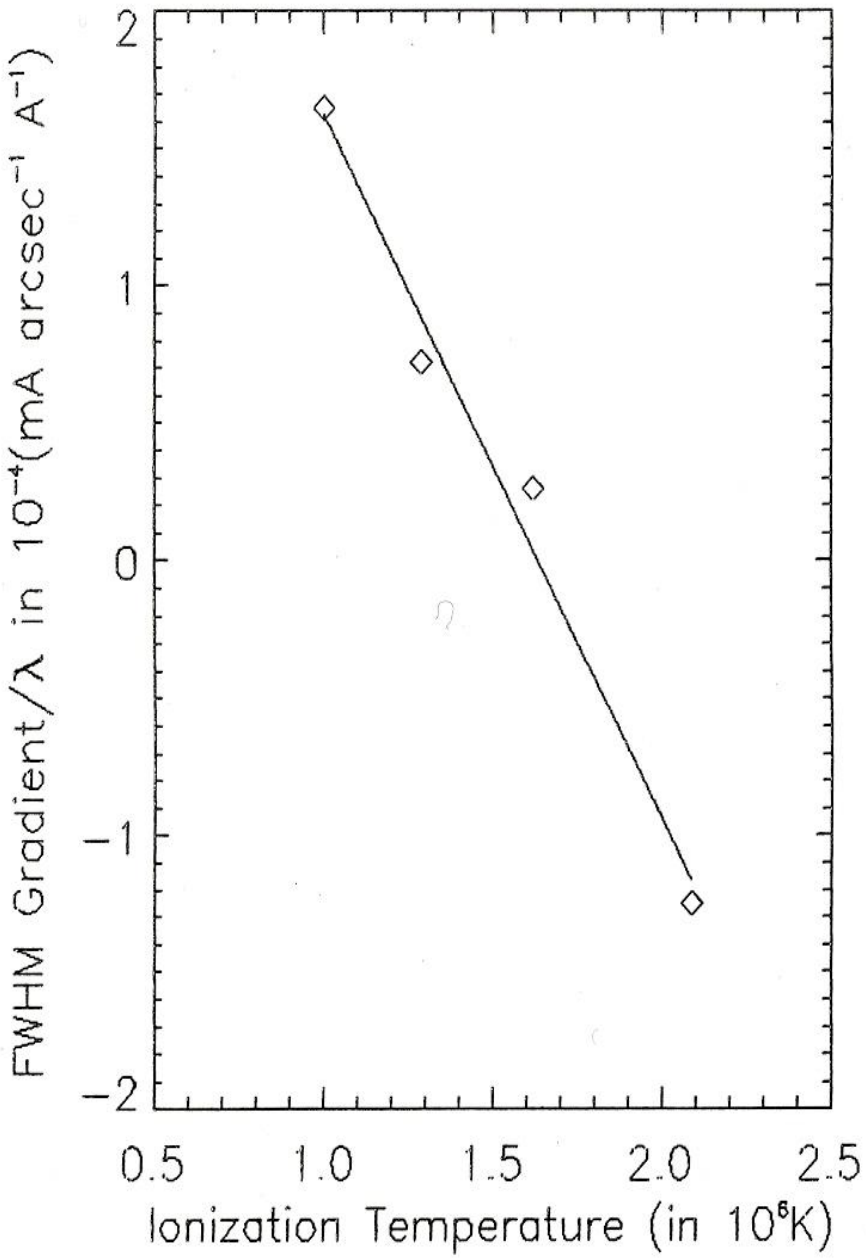


Table 3. Mean value of FWHM (Å) and its gradient (m Å/arcsec) of coronal emission lines

Emission Line	FWHM (50″)	FWHM (100″)	FWHM Gradi.	FWHM Gradi./λ	Ionization temp.(MK)
Red	0.846 ± 0.052	0.898 ± 0.064	1.05	1.65 $\times 10^{-4}$	1.00
7892 Å	1.098 ± 0.087	1.126 ± 0.098	0.57	0.72 $\times 10^{-4}$	1.29
Infrared	1.890 ± 0.103	1.905 ± 0.126	0.29	0.26 $\times 10^{-4}$	1.62
Green	0.822 ± 0.049	0.789 ± 0.063	-0.66	-1.25 $\times 10^{-4}$	2.09


FWHM Gradient/λ in 10^{-4}(mA arcsec^{-1} A^{-1})
2
1
0
−1
−2
0.5
1.0
1.5
2.0
2.5
Ionization Temperature (in 10^6K)

Summary (Line-width variations)

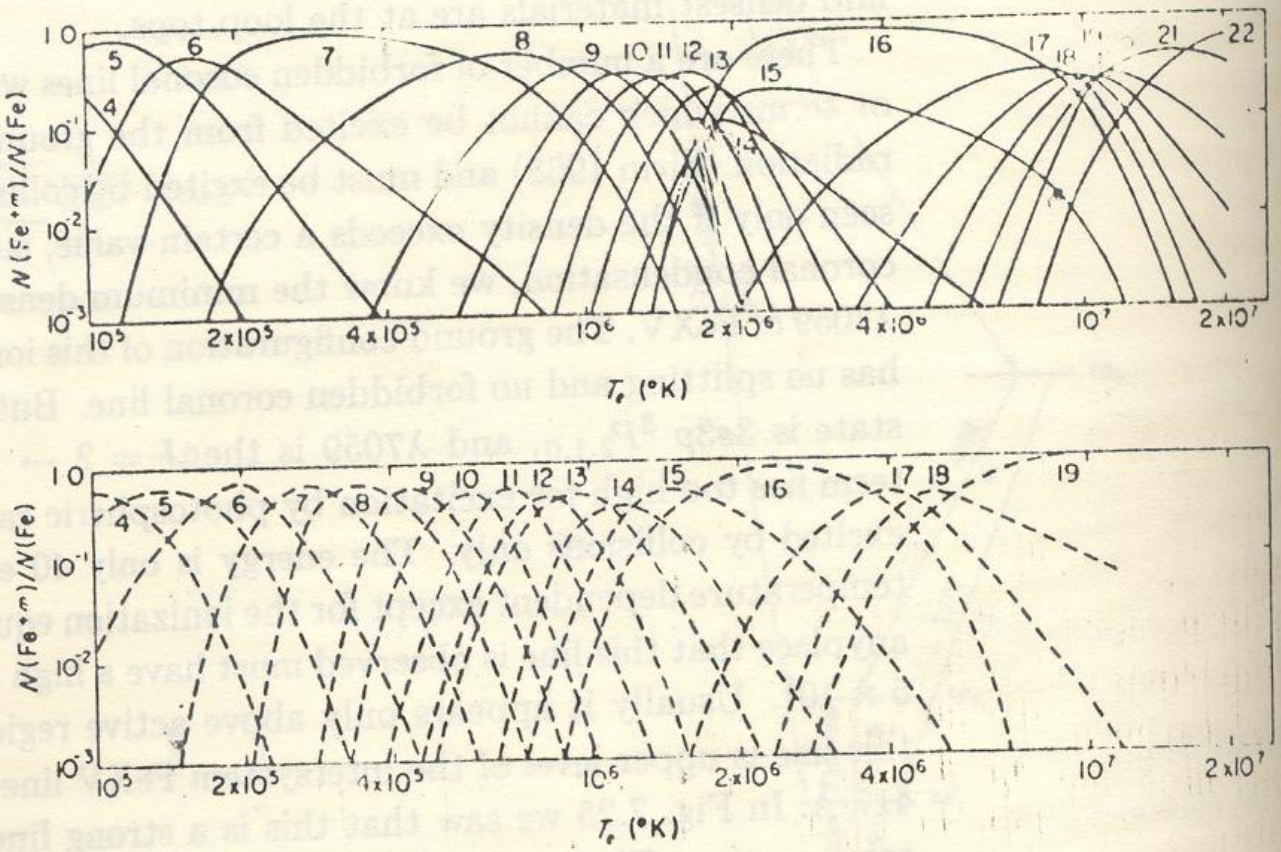
- Most of the coronal loops show decrease in line width of the 5303 line where as increase in width of 6374 line with height above the limb. The 7892 line show increase with height but with less slope as compared to 6374 line. The 10747 show negligible change with height
- All these observations indicate that variation in line width is related with the temperature of the ion the line represents
- The emission line with temperature of maximum abundances greater than 1.6 MK show decrease in line width and less than 1.6 MK show increase in line width with height
- The slope of variation depends on the associated temperature and is negligible for emission line around 1.6 MK

Continue

- The trend in the variation of line width is independent of the shape, size, topology of the coronal loops. To explain it further, line width of the 5303 line decreases in all types of loops such as small or big; open or closed; face-on or end-on; radial or non-radial and that of 6374 increases with height. The magnitude of variation may be different for different coronal loops, because it may depend upon the underlying magnetic field, density, temperature etc.
- The FWHM of [Fe x] and [Fe xiv] emission lines do not show change with height after a distance of about 250 arc sec and normalized ratio is 1 suggesting that plasma at larger heights at uniform temperature and non-thermal velocities. The distance may depend on the physical properties of coronal structure.

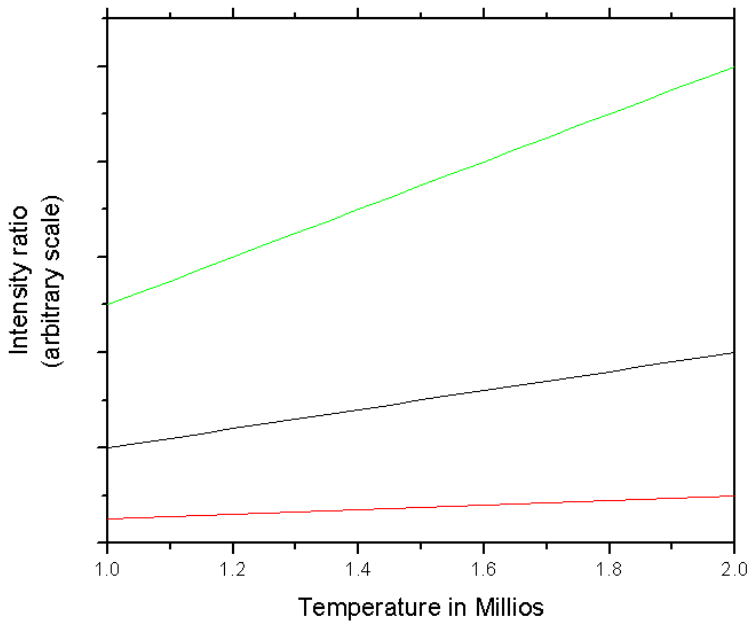
Abundances of Fe ions as a function of Temperature

8.11. Ionization equilibrium of Fe ions. (Jordan 1969)

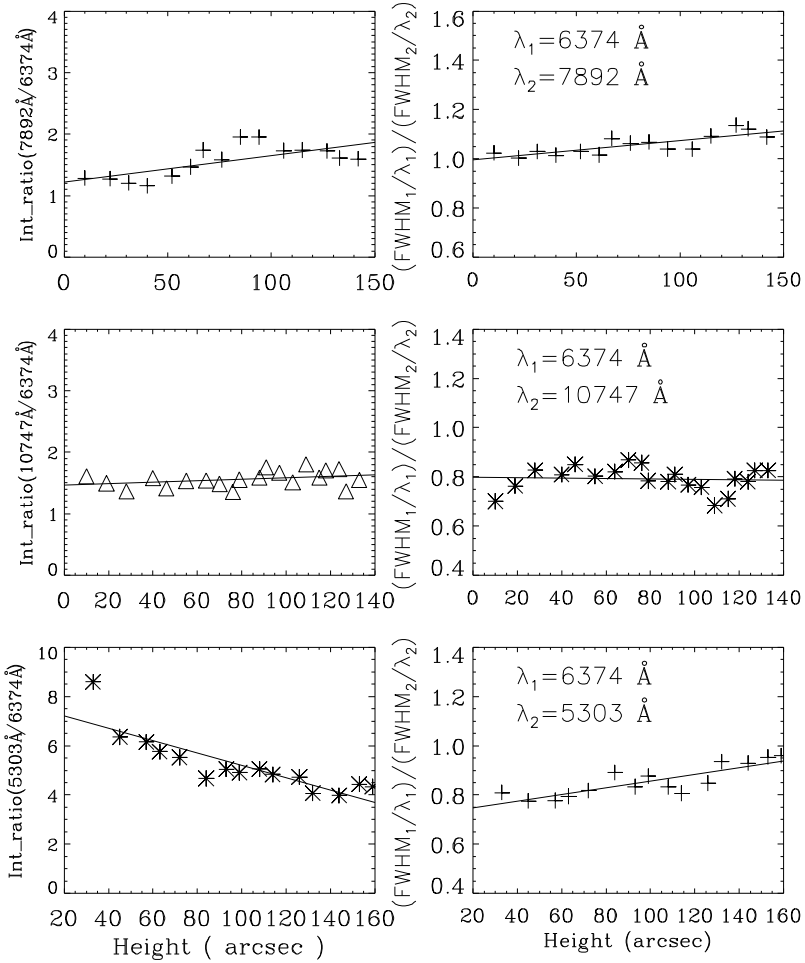


Expected Intensity Ratios

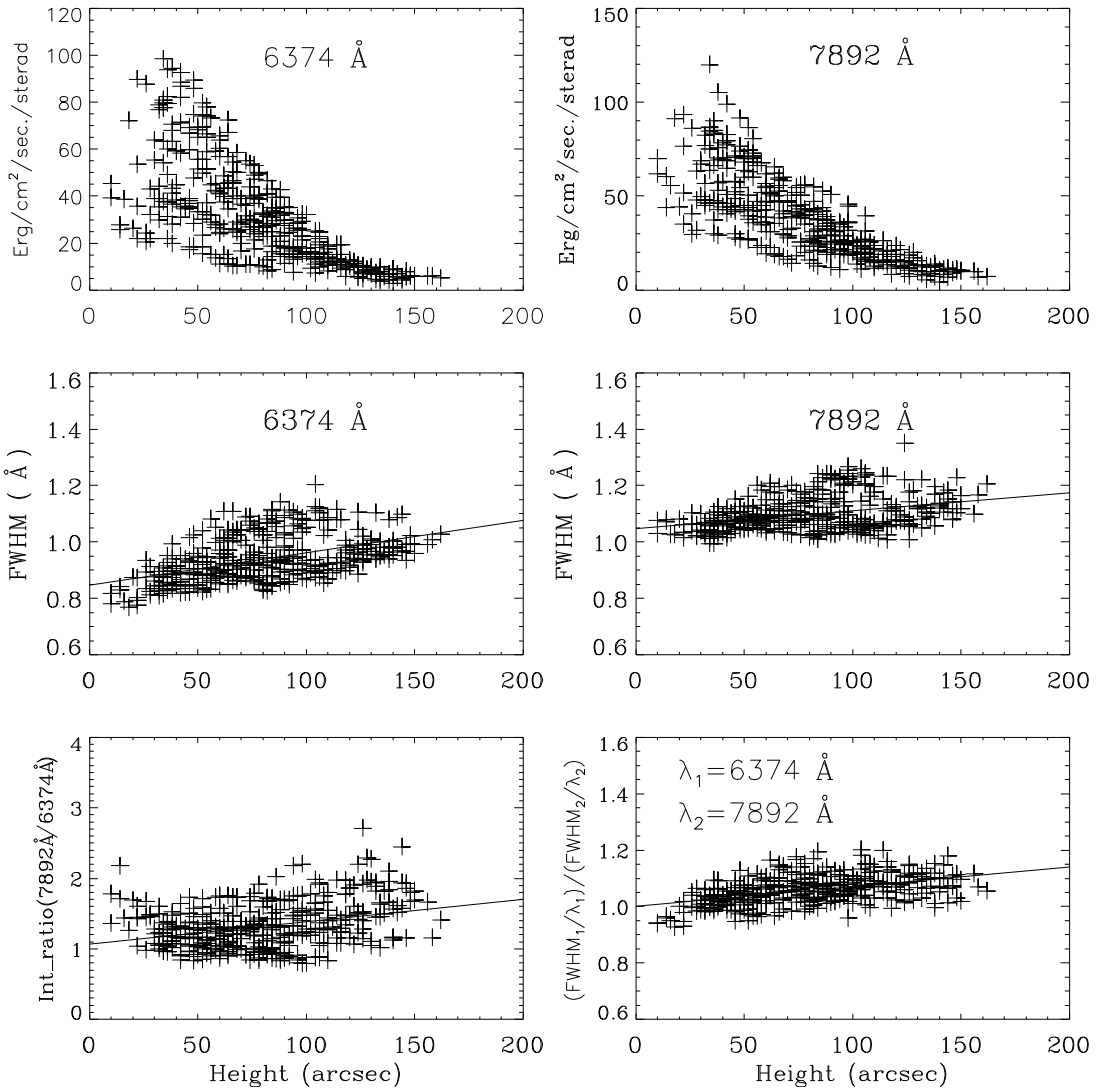
- The abundances of different Fe ions as function of temperature indicate that
- Intensity ratio of [Fe xi] to [Fe x] emission line should increase if the thermal temperature increases
- Intensity ratio of [Fe xiii] to [Fe x] emission line should increase steeply if the thermal temperature increases
- Intensity ratio of [Fe xiv] to [Fe x] emission line should increase more steeply if the thermal temperature increases



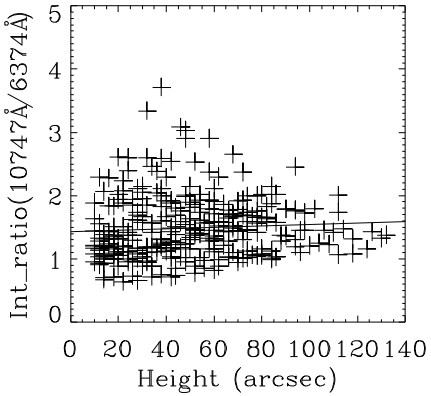
Typical variation of intensity ratios of emission lines with height for individual coronal loops as Seen in the previous slide by + mark

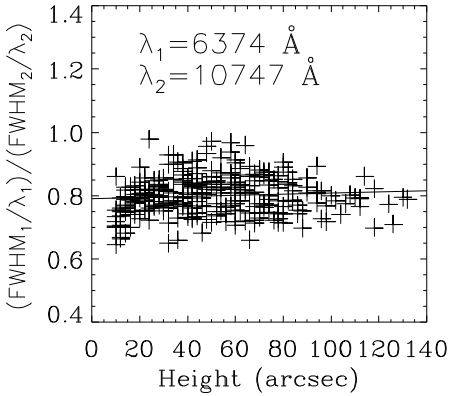


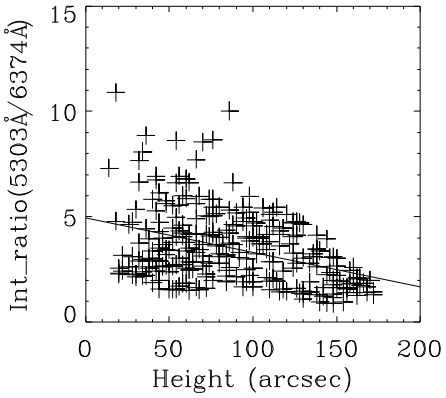
Variation of line-widths, intensity and intensity ratios of [Fe xi] and [Fe x] emission lines as function of height

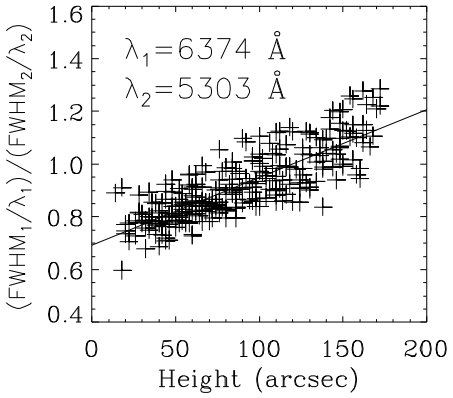


Variation of intensity ratios and line-widths of [Fe xiii] to [Fe x] emission lines as function of height and also of [Fe xiv] to [Fe x]









Observed Intensity Ratios

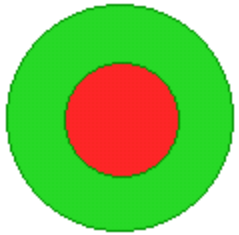
- The intensity ratio of [Fe xi] to [Fe x] line generally increases with height above the limb indicating increase in temperature with height. This agrees with the findings of Kano and Tsuneta showing that emission measure is highest at the loop top.
- The intensity ratio of [Fe xiii] to [Fe x] line shows small variation with height above the limb. One would have expected a larger variation with height considering the similar change in temperature with height as observed from the variation in [Fe xi] to [Fe x] line ratio and the abundances of ions as a function of temperature.
- To our surprise the intensity ratio of [Fe xiv] to [Fe x] line decreases with height above the limb. Considering the above mentioned logic it should have increased with height much steeply. The decrease in this intensity ratio implies the loop top is cooler if observed in [Fe xiv] emission line.

Discussions

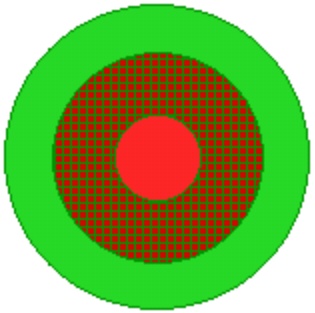
- The observed variations considering one line at a time can be explained
- The increase in line width of [Fe x] line can be explained in terms of increase in the non-thermal velocity due to the existence of waves as has been done most of the time in case of this emission line and similar other EUV emission lines.
- Similarly the decrease in line width of [Fe xiv] with height can be explained in terms of dissipation of waves
- The assumption here is that the different type of plasma behave differently but we have shown that the different temperature plasmas are correlated and co-exist.

Continue

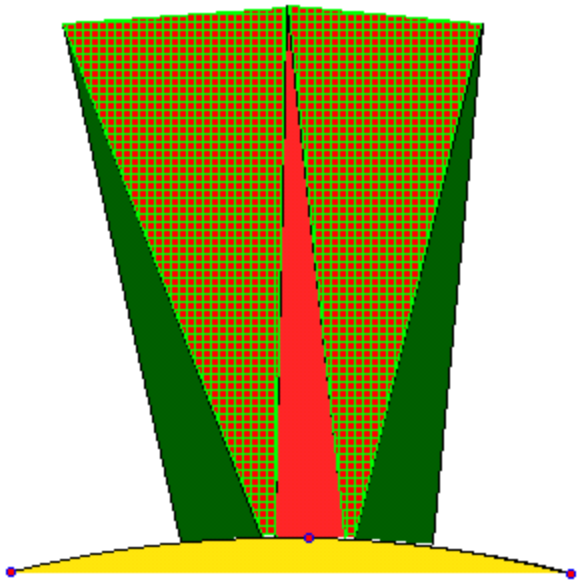
- The monotonic increase in temperature or non-thermal velocity with height above the limb can not explain the observed variations in line widths and intensity ratios with height in all the lines simultaneously. The observed variations can be explained if we assume that the thin coronal loops are not magnetically shielded. The different temperature plasma interact with each other, probably due to collision and the whole of plasma attains uniform temperature and non-thermal velocity at larger heights. This is an empirical model and has the difficulty in explaining the collision between low density plasma at high temperatures.

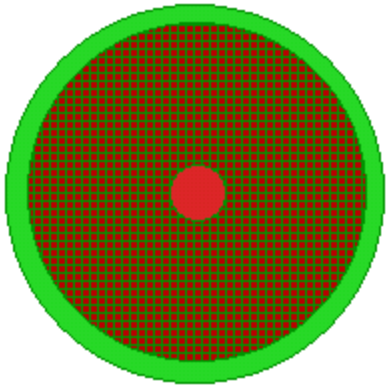


Near Limb

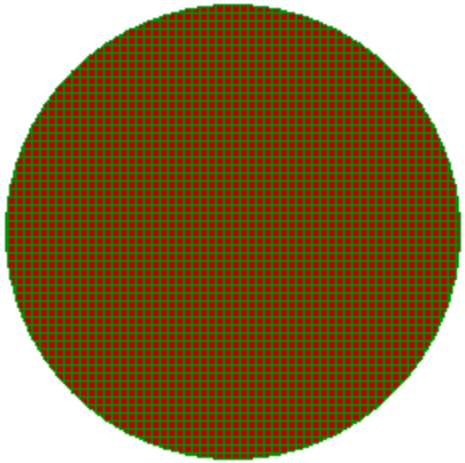


~ 50"





~ 100"



~ 200"

THANK YOU

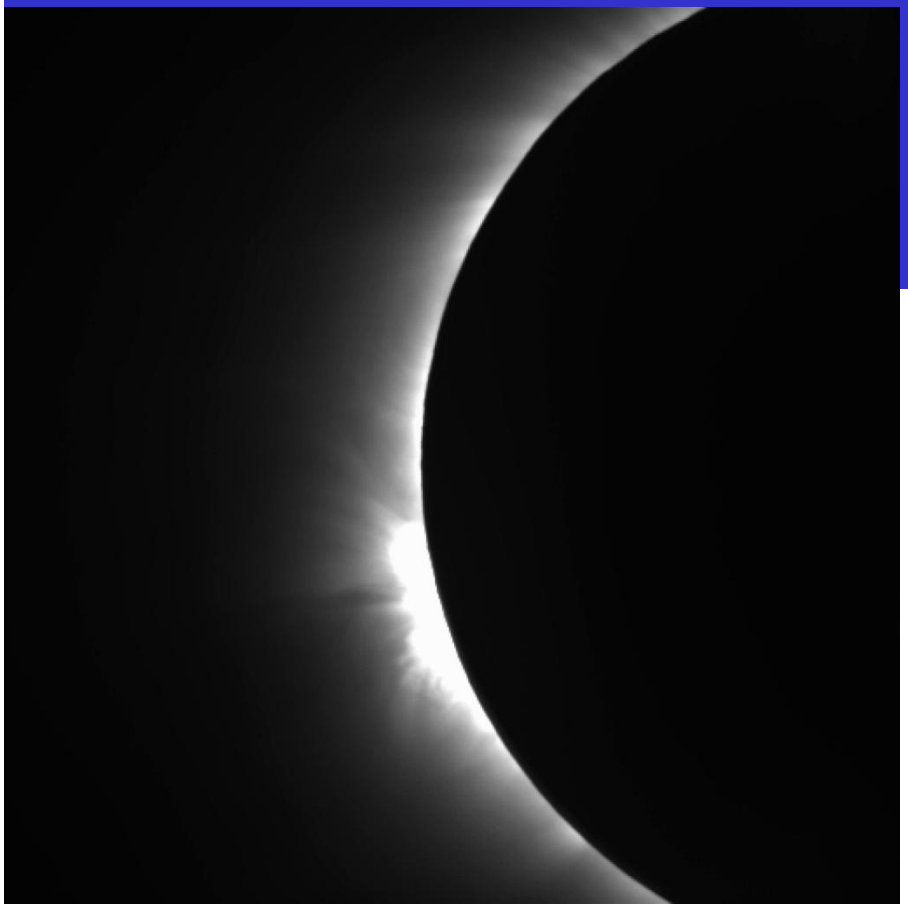


IMAGE TAKEN WITH RED FILTER, 2K X 2K CCD, 4 X 4 BINNING,EXPOSURE TIME 300ms DURING THE TOTAL SOLAR ECLIPSE OF MARCH 29, 2006