PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Spectroscopic Studies of the Solar Corona at X-Ray Wavelengths [and Discussion]

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Spectroscopic studies of the solar corona at X-ray wavelengths

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The spatial distribution of the emission in several X-ray lines is discussed with emphasis on temperature dependence and association with active regions. New results are presented for the trio of helium-like O VII lines which demonstrate (1) a spatial variation in the density dependent forbidden to intersystem line ratio, and (2) a strong spatial variation in the intensity of the O VII resonance line relative to the optically forbidden transitions. The second effect appears to be caused by resonance scattering by material in the line of sight.

Introduction

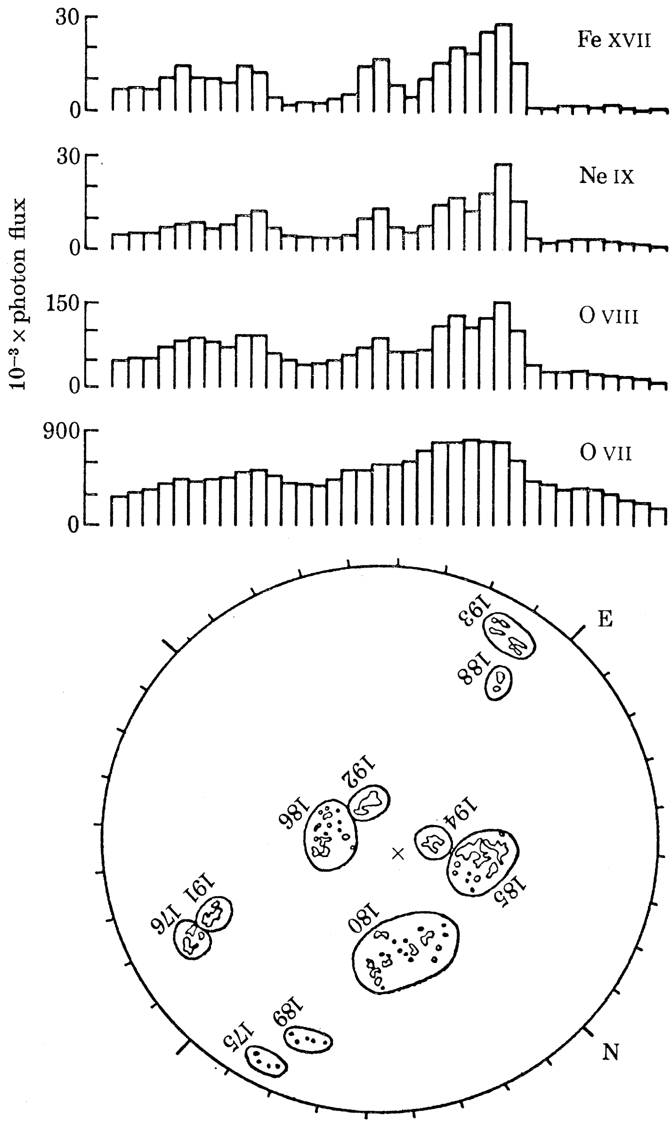
The solar corona represents an insignificant fraction of the mass of the Sun and its radiation makes but a tiny contribution to the solar constant. Even so, the coronal emission dominates the solar spectrum at short wavelengths. The interested reader is directed to reviews by Culhane & Acton (1974), Doschek (1972), Parkinson (1974), Walker (1972), and recent papers by Walker, Rugge & Weiss (1974*a*, *b*, *c*), Parkinson (1973, 1975), Doschek, Meekins & Cowan (1973), and Neupert, Swartz & Kastner (1973) for background information on solar X-ray spectroscopy.

It is the purpose of this paper to present some recent results from spectroscopic studies of the corona at X-ray wavelengths: new experimental information on the spatial distribution of emission from several different X-ray lines, the first conclusive observation of a decrease in the forbidden to intersystem line ratio of O VII due to line formation in a dense region, and the discovery of a spatial variation of the ratio of the triplet series lines to the singlet resonance line of O VII. The latter effect may be associated with resonance scattering by O VII ions in the line of sight.

Spatial distribution of resonance line emission

X-ray photographs of the solar corona, such as have been presented by Vaiana at this meeting, have provided detailed information on the form and intensities of the structures which comprise the X-ray corona. The papers by Vaiana *et al.* (1973*a*, *b*) summarize the results of many years of solar X-ray photography and identify and illustrate six classes of coronal X-ray structures. For understanding the physical conditions within the observed coronal structures, it is helpful if these broad-band X-ray photographs are supplemented with spectroscopic measurements. For example, figure 1 illustrates the variation of emission in four important X-ray lines across the disk of the Sun. These observations were obtained with an improved version of instrumentation described by Acton *et al.* (1972) where the observing technique is explained. The spatial resolution is set by mechanical collimation to 1.3′ (full width at half-maximum transmission) in the direction of scan across the Sun by the full width of the disk in the other direction.

Each of these X-ray lines may be formed over a range of temperatures spanning several million kelvins with the temperature of peak emissivity increasing from O VII to Fe XVII. For the purposes of this discussion, it will suffice to point out the close association of the higher temperature lines with active regions as indicated on the chromospheric calcium plage drawing. In particular, note the dramatic decrease in the Fe XVII and Ne IX emission as the active regions are passed on the right side of figure 1. In anticipation of subsequent discussions of the O VII line ratios, it should be pointed out that most of the radiation observed in the first three bars on the left of the histogram is associated with a broad region just on the west limb. This region does not show on the calcium plage drawing. Also, the brightest feature observed in the Ne IX and Fe XVII lines is associated with McMath region 185 in the NE near central meridian, the most active area on the disk at the time.



McMath calcium plage

FIGURE 1. The distribution of emission across the disk of the Sun in the resonance lines of Fe XVII (1.50 nm), Ne IX (1.35 nm), O VIII (1.90 nm) and O VII (2.16 nm). The data were acquired in the course of a rocket flight on 18 January 1973. Each bar of the histograms is approximately one-third of the total angular width of the collimator field of view in the direction of scan and represents a four second period of time. The McMath calcium plage map, taken from *Solar–Geophysical Data*, is oriented such that the scan proceeded from left to right and the collimator field of view at any time was a vertical strip across the disk.

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Culhane & Acton (1974) have presented other Lockheed rocket results similar to figure 1 but utilizing two dimensional collimation. Those data show the higher temperature emissions to be strongly concentrated towards the core of the active regions. The lower sensitivity resulting from the 2-dimensional collimation permitted detection of only the O VII and O VIII lines outside of active regions.

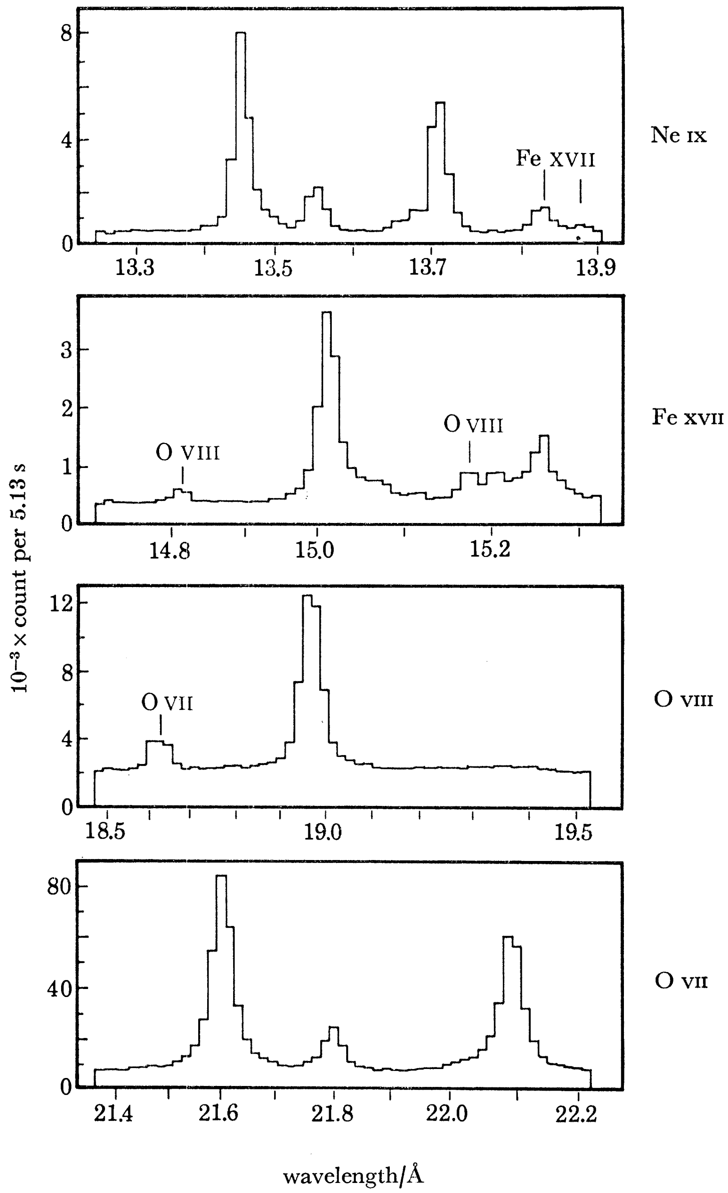

FIGURE 2. Spectra acquired during the rocket experiment of 18 January 1973. Four separate Bragg spectrometers with a common field of view scanned stepwise through their spectral ranges once each second. The spectra presented here were summed over the entire flight.

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Spectroscopic results

For investigating coronal physics, it is not always necessary to record the entire X-ray spectrum. It is often preferable in a rocket experiment of limited duration to concentrate on narrow spectral intervals containing the emission lines of interest. Figure 2 is an example of such spectra, accumulated during the flight of 18 January 1973 for which the spatial distribution of the four resonance lines was presented in figure 1. In the following sections we will limit our discussion to the O VII data from this experiment.

The density sensitive line ratio

Gabriel & Jordan (1969*a*, *b*) first identified the ^3S–^1S (F) transition in solar spectra and recognized that the intensity ratio of this line to the ^3P–^1S (I) line should be sensitive to electron density because of collisional depopulation of the long-lived ^3S state. Subsequent publications (Freeman *et al.* 1971; Gabriel 1972; Mewe 1972; Gabriel & Jordan 1973) have further developed the theory and improved the accuracy of the atomic parameters involved. It appears that the electron densities required to produce a measurable deviation in this line ratio are at the upper limit of those expected to occur in the line forming regions of the solar corona. Up to this time, conclusive deviations of this line ratio from the low density limit have not been observed for the non-flaring Sun, at least partly because of poor quality of the experimental data (Walker & Rugge 1970; Acton, Catura, Meyerott & Culhane 1971). The data presented below are superior to earlier results for investigating this problem because the statistical quality and spectral resolution are good and the only variable parameter throughout the data set is the position of the field of view on the Sun.

The bottom section of figure 3 shows counts of the O VII resonance lines collected for each 4 s data sample. The left-hand bottom display is the same data presented in the O VII panel of

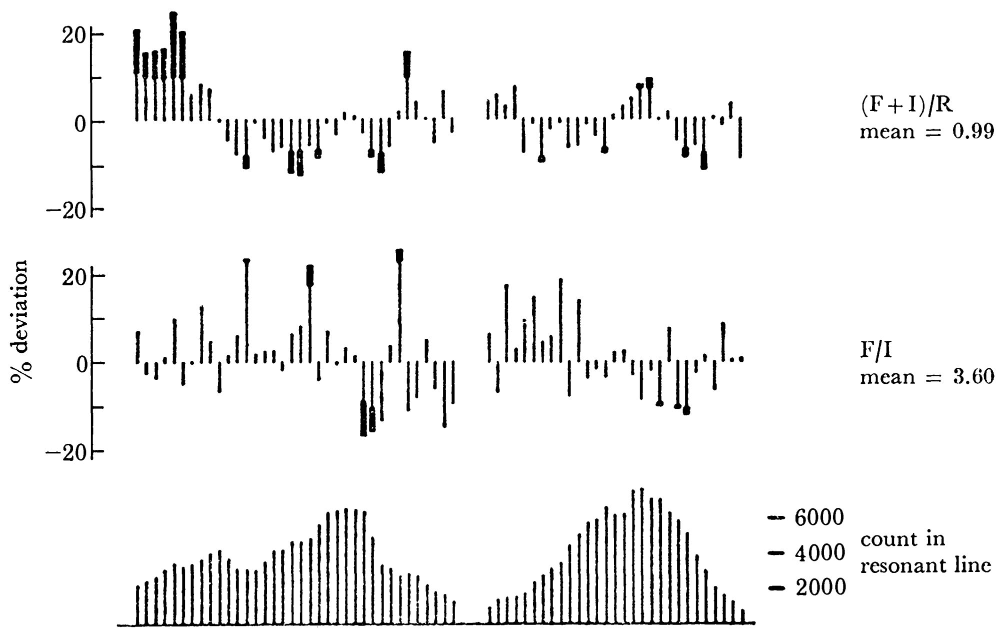

FIGURE 3. Analysis of the O VII line ratios from the flight of 18 January 1973. The group of data on the left corresponds to the first scan of the disk, presented in figure 1. The second, north to south, scan of the disk is summarized in the group of data on the right. The rocket was rolled 46° between the two scans. Further description may be found in the text.

figure 1. The right-hand portion of figure 3 shows additional data collected during the second half of the rocket flight when the field of view of the spectrometers was swept across the Sun from north to south.

The middle portion of figure 3 shows the percent deviation of the F/I ratios from a mean determined from the entire data sample. When this deviation exceeds 2σ, the bar is drawn heavy black. (The σ used for this purpose is that derived from the counting statistics of each individual data sample rather than the standard deviation of the mean which is, of course, much smaller.) These data have been corrected for background and all known instrumental effects. The instrumental resolution was inadequate to permit correcting for satellite line blends, so an additional random error of 2 % above the counting statistics was included when computing the standard error of each datum. The value of the mean F/I ratio is 3.60 and is dependent on the choice of background. The more significant result is the deviation from this mean from point to point on the Sun and this result is nearly independent of possible residual systematic error.

The first scan across the Sun provides the best data for isolating localized high-density line forming regions because the payload was oriented so as to minimize superposition of different active regions in a single field of view. Note that about $\frac{3}{4}$ of the way through the first scan there are three adjacent data samples showing a 15 % or larger depression of the F/I ratio. These points are significant at the 3.5, 3.0 and 2.0 σ level, respectively. The probability of this association occurring by chance is 2×10^{-6}.

Because of the superposition of sources in the field of view on the second scan, it is difficult to definitely locate the dense source region. The data are consistent, however, with identifying the region with the eastern-most portion of McMath region 185, the brightest e.u.v. and X-ray feature on the disk at the time.

Since dense regions are included in the mean F/I ratio, it will be below the true low density limit. Furthermore, low density emitting material within the field of view will tend to dilute the contrast of the high density feature so that we estimate a true depression of the F/I ratio of at least 20 %. We ignore the weak temperature dependence of the F/I ratio discussed by Gabriel & Jordan (1973) and accept their statement that a 10 % depression of the ratio corresponds to an electron density of 3×10^9 cm^{-3}. Then, for purely collisional excitation, the density may be expressed in terms of the F/I ratio as:

$$N = 2.7 \times 10^{10} (R_0/R - 1)\ \text{cm}^{-3},$$

where R_0 is the F/I ratio in the low density limit and, here, R is the observed F/I ratio. In our case, R_0/R equals 1.25 so that:

$$N \approx 7 \times 10^9\ \text{cm}^{-3}.$$

This density is high but not unreasonable. A more important result is to have demonstrated the applicability of the theory of Gabriel & Jordan for diagnosis of solar plasmas – provided that the experimental data are of sufficient quality.

Resonance line absorption

Questions of X-ray self-absorption and radiative transfer effects have been neglected in all recent solar X-ray research. It has been universally assumed that all X-ray lines are optically thin even though the pioneering theoretical work of Elwert (1954, 1956) indicated the possibility of optical depths greater than unity for some lines.

The O VII data from our 18 January 1973 rocket experiment exhibit a spatial variation of the resonance line (^1P–^1S) intensity relative to the optically forbidden triplet to singlet transitions (^3P–^1S and ^3S–^1S) which we believe is caused by resonance scattering. The top section of figure 3 shows the variation of the forbidden (F, ^3S–^1S) plus the intersystem (I, ^3P–^1S) line intensities to the resonance (R, ^1P–^1S) line for all of the data from the rocket flight. These data have been analysed and presented in the same way as the F/I ratios discussed earlier. Aside from statistical differences and variations of the F/I ratio itself, we find the F/R and I/R ratios to be entirely analogous, therefore we present the combined (F + I)/R ratio.

Most of the radiation observed at the start of scan 1 originated in McMath region 171, an old region spanning 30° in longitude, which was just crossing the west limb at the time of our flight, and region 176 at 55° past central meridian. Although the superposition of sources on the second scan reduces the contrast, the positive deviations just past the centre of scan two are consistent with these locations for the strong positive deviation regions of scan one. The single strong positive deviation near the end of scan one seems to be associated with McMath region 197 which was just beyond the east limb.

The association of resonance line weakening with sources near the limb is immediately suggestive of absorption or resonance scattering rather than some unusual excitation effect. This geometry permits the maximum amount of material in the line of sight. Furthermore, O VII is the predominant oxygen ion between 1.8×10^5 and 2×10^6 K so that essentially all of the oxygen in the line of sight will contribute to resonance scattering even though its self-emissivity may be low. As both the F and I transitions are optically forbidden, the absorption optical depth for these lines will be many orders of magnitude below that of the resonance line. They, therefore, serve as a convenient reference against which to measure the diminution of the resonance line.

Again, as in the F/I line ratio analysis, the absolute value of the line ratio is not as important as the spatial variation of the ratio. However, it may be worth noting that the mean values given in figure 3 for both ratios should be good to better than 10 %.

The data of figure 3 imply a 30 % increase, above the disk centre lower limit, of the (F + I)/R ratio for the western regions. For an approximate analysis, we may consider this as purely an absorption effect corresponding to an optical depth, τ, of about 0.26 in the resonance line. Neglecting re-emission into the line of sight, τ is given by the expression:

$$\tau = \sigma \frac{N_e A_0}{A_e} L,$$

where σ is the absorption cross-section per O VII ion (cm^2); N_e, the electron density (cm^{-3}); A_0, the elemental abundance of oxygen relative to hydrogen; A_e, the number of free electrons per hydrogen atom; L, the absorption path length (cm).

We assume that $A_0 = 3 \times 10^{-4}$ (derived assuming a neon abundance of 6×10^{-5} and the O/N_e abundance ratio of 5, recently published by Acton, Catura & Joki (1975)), $A_e = 1.2$ and that all of the oxygen is in the form of O VII. The line centre absorption cross section is calculated from the expression (Allen 1973):

$$\sigma = \frac{0.0265 f}{\Delta\nu} \mathrm{cm}^2,$$

where $f = 0.7$ is the absorption oscillator strength of the resonance transition and $\Delta\nu$, the Doppler width, is approximately $3 \times 10^{13}\,s^{-1}$ for an assumed temperature of 1.6×10^6 K

We may combine these expressions to solve for $N_e L$, the number of electrons per square centimetre of column along the absorbing line of sight:

$$N_e L = 1.7 \times 10^{18}\,\text{cm}^{-2}.$$

This is commensurate with the value of $N_e L$ derived using the spherically symmetric coronal model of Withbroe (1972) with an electron density of $10^8\,\text{cm}^{-3}$ at the base of the corona for a source region more than 55° from disk centre.

This approximate model indicates that scattering of the X-ray resonance line is the probable cause of its variation in intensity relative to the forbidden transitions. It follows that radiative transfer effects should not be ignored when interpreting X-ray resonance line intensities. Correspondingly, the optically forbidden transitions of the helium-like ions will now be of even greater importance for plasma diagnostics because they are not only density sensitive but are also independent of the complications of radiative transfer.

Summary and conclusions

We have attempted to demonstrate the role of high resolution X-ray spectroscopy in coronal research. It should be clear from the discussions of this meeting that both spectroscopy and broad-band imagery will be required to pursue these studies until such a time that the spectroscopic measurements can obtain sufficiently fine spatial resolution and still maintain appropriate sensitivity.

In the forgoing sections we have utilized data with fair spatial resolution and good statistical quality to demonstrate two important new experimental results:

(1) For O VII, at least, the density dependence of the forbidden to intersystem line ratio of helium-like ions is observable and usable for coronal studies.

(2) Radiative transfer effects due to resonance scattering must be taken into account in interpreting the intensity of X-ray resonance lines. The forbidden transitions serve as effective indicators of the importance of this effect for the helium-like ions.

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References (Acton & Catura)

Acton, L. W., Catura, R. C. & Joki, E. G. 1975 *Astrophys. J.* **195**, L93–L95.
Acton, L. W., Catura, R. C., Meyerott, A. J., Wolfson, C. J. & Culhane, J. L. 1972 *Solar Phys*, **26**, 183–201.
Acton, L. W., Catura, R. C., Meyerott, A. J. & Culhane, J. L. 1971 *Nature, Lond.* **233**, 75.
Allen, C. W. 1973 *Astrophysical Quantities* 3rd ed., p. 58. London: Athlone Press.
Culhane, J. L. & Acton, L. W. 1974 *A. Rev. Astron. Astrophys.* **12**, 359–381.
Doschek, G. A., Meekins, J. F. & Cowan, R. D. 1973 *Solar Phys.* **29**, 125–142.
Doschek, G. A. 1972 *Space Sci. Rev.* **13**, 765.

Elwert, G. 1954 *Z. Naturf.* **9** *a*, 637–653.
Elwert, G. 1956 *Z. Astrophys.* **41**, 67–83.
Freeman, F. F., Gabriel, A. H., Jones, B. B. & Jordan, C. 1971 *Phil. Trans. R. Soc. Lond.* A **270**, 127–133.
Gabriel, A. H. & Jordan, C. 1973 *Astrophys. J.* **186**, 327–333.
Gabriel, A. H. 1972 *Atoms and molecules in astrophysics* (ed. T. R. Carson & M. J. Roberts), pp. 311–320. N.Y.: Academic Press.
Gabriel, A. H. & Jordan, C. 1969 *a* *Nature, Lond.* **221**, 947.
Gabriel, A. H. & Jordan, C. 1969 *b* *Mon. Not. R. Astr. Soc.* **145**, 241.
Mewe, R. 1972 *Solar Phys.* **22**, 114–118.
Neupert, W. M., Swartz, M. & Kastner, S. O. 1973 *Solar Phys.* **31**, 171–196.
Parkinson, J. H. 1973 *Astron. Astrophys.* **24**, 215.
Parkinson, J. H. 1974 *Proc. of IAU Symp. No.* 68 *on Solar γ-, X- and EUV-Radiation*, Buenos Aires.
Parkinson, J. H. 1975 (Submitted to *Solar Phys.*)
Vaiana, G. S., Davis, J. M., Giacconi, R., Krieger, A. S., Silk, J. K., Timothy, A. F. & Zombeck, M. 1973 *a* *Astrophys. J.* **185**, L 47–L 52.
Vaiana, G. S., Krieger, A. S. & Timothy, A. F. 1973 *b* *Solar Phys.* **32**, 81–116.
Walker, A. B. C., Jr., Rugge, H. R. & Weiss, K. 1974 *a* *Astrophys. J.* **188**, 423–440.
Walker, A. B. C., Jr., Rugge, H. R. & Weiss, K. 1974 *b* *Astrophys. J.* **192**, 169–180.
Walker, A. B. C., Jr., Rugge, H. R. & Weiss, K. 1974 *c* *Astrophys. J.* **194**, 471–482.
Walker, A. B. C., Jr. 1972 *Space Sci. Rev.* **13**, 672.
Walker, A. B. C., Jr. & Rugge, H. R. 1970 *Astron. Astrophys.* **5**, 4.
Withbroe, G. L. 1972 *Solar Phys.* **25**, 116–126.

Discussion

G. Vaiana

For your determination of the O/Ne abundance ratio are you sure that the O VIII and Ne IX intensities can be attributed to the same physical region on the Sun?

L. W. Acton

We believe we can be sure of this for two reasons: (1) for 15 of the 25 independent observations used in this analysis, 2 dimensional collimation was employed; (2) for the normal range of temperature encountered in non-flaring active regions O VIII and Ne IX line emission will both be produced. These are the types of regions to which the observations refer.