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New Observations of Fe XVII in the Solar X-ray Spectrum

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Summary. New observations of the Fe XVII lines between 13 and 18 Å in the solar X-ray spectrum are presented. The observations were made with a high resolution, collimated, crystal spectrometer, and all of the Fe XVII lines are clearly resolved, including the $2p^6\,{}^1S_0 - 2p^5\,3s\,{}^3P_1$ and ${}^3P_2$ lines near 17 Å. The relative intensities of the Fe XVII lines are in good agreement with the calculations of Loulergue and Nussbaumer (1973) which include cascade processes. A number of satellite lines of the form $2p^6 \cdot nl - 2p^5\,3\binom{d}{s} \cdot nl, n \geqq 3$, in Fe XVI are also observed.

Key words: solar corona – X-rays – Fe XVII

1. Introduction

In the last few years several rocket and satellite experiments have observed the solar X-ray spectrum in the wavelength range below 25 Å, and have shown the Fe XVII lines to be intense features. Calibrated crystal spectrometers have been used by Blake *et al.* (1965), Evans and Pounds (1968), Walker and Rugge (1969) and Parkinson (1971a), and a grazing incidence spectrograph by Freeman and Jones (1970). Most of the early instruments viewed the whole sun with a small effective area and moderate spectral resolution, and gave spectra in which some of the Fe XVII lines were not clearly resolved.

Early theoretical studies of Fe XVII (e.g. Garstang, 1966; Froese, 1967) did not allow for some of the energy levels being populated by cascades from higher levels. For some lines there were substantial disagreements between the calculations and observations.

Recently both the calculations and observations have been significantly improved. In the preceding paper the calculations of Loulergue and Nussbaumer (1973) take account of cascading processes. In this paper new observations of the Fe XVII lines, obtained with a much higher resolution instrument than any used previously in this wavelength range, are presented. Together these results help to remove most of the previous disagreements between theory and observation.

2. Observations

The observations were made with a Bragg crystal spectrometer which has a greater sensitivity and resolution than the instrument described previously (Parkinson, 1971a). The new instrument contained three crystals each with an effective area of 50 cm^2 and a field of view restricted to 3′ FWHM. The Bragg angle readout was with a 14-bit shaft encoder, allowing the accurate determination of absolute wavelengths.

The spectrometer was launched on a Sun-stabilised Skylark rocket, SL 1101, from Woomera, South Australia, at 0529 UT on 30 November 1971. The X-ray spectra presented here are of an active region near N 15 W 35 (McMath Region 11621). The complete spectrum is presently being analysed and a full report will be published in due course. The present paper deals only with the Fe XVII lines; an analysis of the Mg XI lines has already been published (Parkinson, 1972).

Figure 1 shows a section of the spectrum between 13 and 18 Å obtained with a KAP (potassium acid phthallate) crystal. In this figure each Fe XVII line has been fitted with a triangle, which approximates to a convolution of the collimator transmission profile and the crystal rocking curve, after neglecting the extended wings. A discussion of the problems involved in identifying the Fe XVII lines is deferred to Section 3. Also indicated in Fig. 1 are lines of Ne IX, O VIII and Fe XVIII.

Listed in Table 1 are the transitions involved for the eight Fe XVII lines indicated in Fig. 1, together with the measured wavelengths and count rates. Loulergue and Nussbaumer compared intensities, in erg cm^{-2} s^{-1}, relative to the 15.01 Å line, as the $2p^5\,3d\,{}^1P_1$ level is populated to 90% by collisional excitation from $2p^6\,{}^1S_0$. The count rates have therefore been converted to energy units as the integrated reflectivity of the crystal and the photon detection efficiency of the proportional counter are both known as a function of wavelength. Recently the reflectivity of KAP has been measured by Leigh and Evans (1972) using a double crystal spectrometer and correcting these results to parameters applicable to single crystals. These values are approximately 50% higher and decrease more slowly with increasing wavelength than the values used by previous

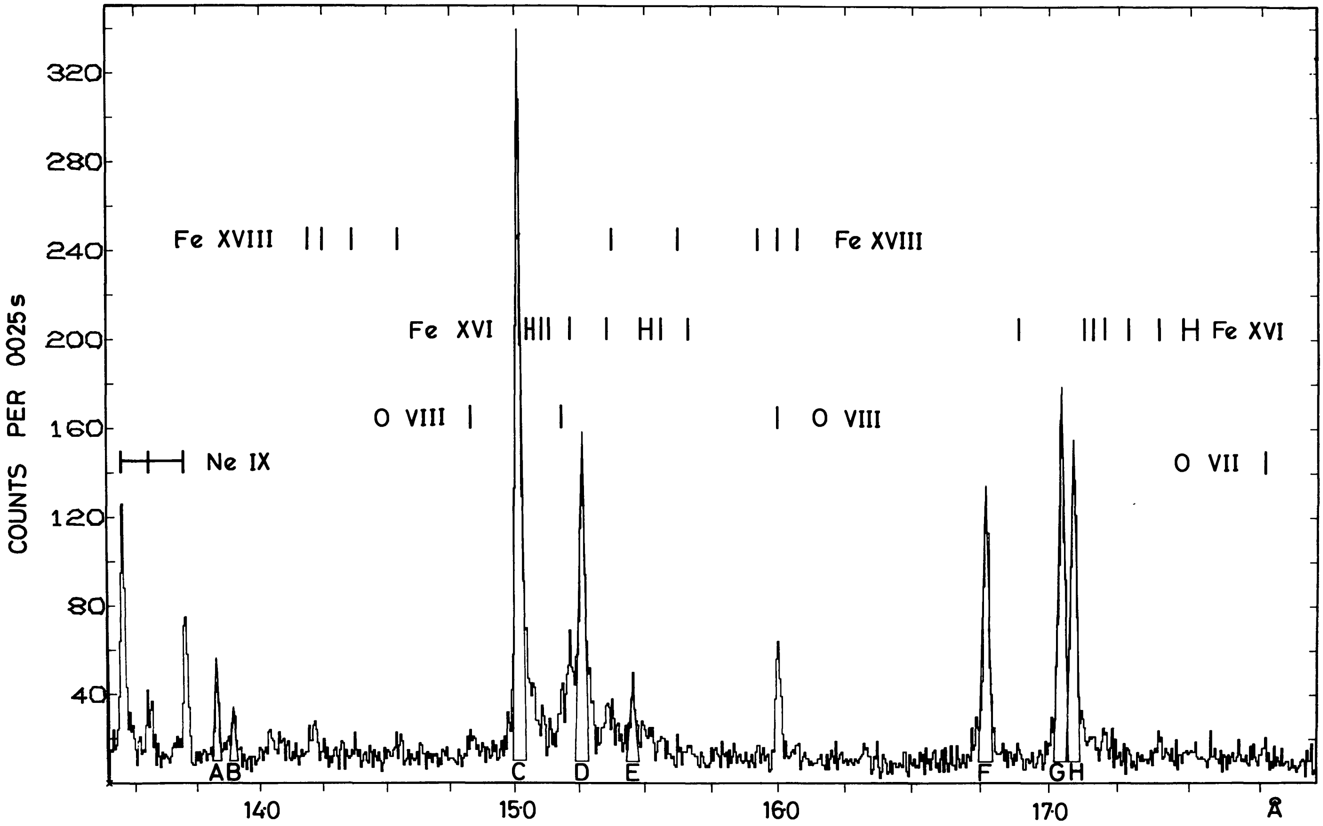

Fig. 1. The X-ray spectrum of a solar active region between 13 and 18 Å, obtained with a collimated KAP crystal spectrometer. Note the importance of the Fe XVII lines which are marked A, B, C, ... H

Table 1. Comparison of observed and calculated Fe XVII line ratios

	Transition: Lower level	Transition: Upper level	Measured wavelength Å	Integrated reflectivity[a] $\times 10^{-5}$ rad	Line intensity counts	Ratio[b] This work	Ratio[b] calculated[c]
A	$2s^2\,2p^6\ {}^1S_0$	$2s\,2p^6\,3p\ {}^1P_1$	13.824	6.2	118	0.07	0.15
B		${}^3P_1$	13.888	6.2	65	0.04	0.10
C	$2s^2\,2p^6\ {}^1S_0$	$2p^5\,3d\ \ {}^1P_1$	15.013	5.8	1320	1.00	1.00
D		${}^3D_1$	15.259	5.7	600	0.47	0.37
E		${}^3P_1$	15.449	5.6	136	0.11	0.08
F	$2s^2\,2p^6\ {}^1S_0$	$2p^5\,3s\ \ {}^1P_1$	16.769	5.3	550	0.57	0.54
G		${}^3P_1$	17.041	5.2	748	0.81	0.97
H		${}^3P_2$	17.086	5.2	590	0.64	0.74

[a]) Leigh and Evans (1972).
[b]) Ratios of line intensities in erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
[c]) Loulergue and Nussbaumer (1973).

experimenters. The proportional counter had a depth of 2 cm filled with 90 : 10 argon : methane and a window of 4 μ polypropylene.

Table 1 compares the observed and calculated Fe XVII intensities relative to λ 15.01 Å. There is now good agreement between the observations and the calculations indicating the importance of correctly identifying the Fe XVII lines and including cascade processes in the calculations.

3. Discussion of the Line Identifications

3.1. The $2s^2\,2p^6\ {}^1S_0 - 2s\,2p^6\,3p\ {}^{1,3}P_1$ *Lines between 13.8 and 13.9 Å*

Although the two lines here are 0.060 Å apart they have been the subject of some confusion in the past. In view of this it is quite remarkable that the ratios given in Table 3 of Loulergue and Nussbaumer are in such good agreement.

Blake *et al.* (1965) observed a single line between 13 and 14 Å, at 13.7 Å, which they attributed as basically due to Fe XVII; we now know that the Ne IX triplet dominates this spectral region with a small contribution from Fe XVII. Evans and Pounds (1968) claimed to identify the 13.82 Å Fe XVII line but not the 13.88 Å line, even though they did identify the Ni XIX $2p^6\,{}^1S_0-2p^5\,3s\,{}^1P_1$ line at 13.77 Å. Walker and Rugge (1969) only identified the 13.82 Å line.

Figure 1 shows that all of these lines are now clearly resolved. Two lines occur at 14.04 and 14.08 Å, the expected positions of the Ni XIX $2p^6\,{}^1S_0-2p^5\,3s\,{}^3P_1$ and ${}^3P_2$ lines, but each is approximately three times stronger than would be expected from the 13.77 Å Ni XIX line. A slow scan of the gypsum crystal on SL 1101 through this group of lines with greater sensitivity confirms the low intensity of the 13.77 Å Ni XIX relative to the 13.82 Å Fe XVII line.

3.2. *The* $2p^6\,{}^1S_0-2p^5\,3d\,{}^{1,3}P_1,\,{}^3D_1$ *Lines between* 15.0 *and* 15.5 Å

With moderate resolution the group of lines between 15.0 and 15.5 Å appear badly blended, but dominated by λ 15.01 Å. Blake *et al.* (1965) only identified two lines here, Walker and Rugge (1969) three and Evans and Pounds (1968) four. The grazing incidence spectrograph of Freeman and Jones (1970) also had insufficient resolution to completely resolve all of the lines.

The present spectrum shows λ 15.01 Å as the strongest line here and so is a good choice for a reference line. After allowing for the Fe XVII lines listed in Table 1, the Fe XVIII lines at 15.37, 15.62, 15.92 and 16.07 Å (Fawcett *et al.*, 1967; Cohen *et al.*, 1968; Connerade, 1970) and the O VIII $1s-3p$ line at 16.007 Å and $1s-4p$ at 15.179 Å, there are several unidentified lines. There are at least three lines between 15.04 and 15.15 Å, and a strong line, approximately 0.2 of λ 15.01 Å, at 15.210 Å. Failure to resolve this latter line in previous spectra has increased the relative intensity of λ 15.26 Å. There are also unidentified lines at 15.35, 15.49–15.53, 15.56 and 15.66 Å which have increased previous estimates of the λ 15.45 Å relative intensity. It is suggested that some of these unidentified lines may be satellite lines of the form $2p^6\cdot nl-2p^5\,3d\cdot nl$, n $\geqq 3$ in Fe XVI, analogous to the satellite lines to He-like ions.

3.3. *The* $2p^6\,{}^1S_0-2p^5\,3s\,{}^1P_1,\,{}^3P_{1,2}$ *Lines between* 16.7 *and* 17.1 Å

The situation is a little clearer in this region. The 16.77 Å line is well isolated so it is surprising to find variations of a factor two here in the previous observations. Even though the two lines near 17.1 Å are 0.045 Å apart they have not previously been as clearly resolved as they are in Fig. 1. Only the spectrum of Walker and Rugge (1970) shows even a slightly broadened line. The measured wavelengths of the ${}^3P_1$ and ${}^3P_2$ lines are in slight disagreement with the wavelengths given by Garstang (1966), but there is good agreement with his line spacing. The $2p^6\,{}^1S_0-2p^5\,3s\,{}^3P_2$ transition is a magnetic quadrupole transition and has been studied by Garstang (1969).

The spectrum in Fig. 1 also shows several weak unidentified lines at 16.89, 17.12, 17.15, 17.20, 17.28, 17.39, 17.48–17.52 Å. (The O VII $1s^2-1s\,4p$ line at 17.76 Å indicates that the O VII contribution to the lines at 17.40 and 17.20 Å is small.) Again it is suggested that these lines may be satellite lines of the form $2p^6\cdot nl-2p^5\,3s\cdot nl, n\geqq 3$ in Fe XVI. The laboratory iron-spark spectra of Feldman and Cohen (1968) also show several lines in this region, some of which agree in wavelength with the lines observed here. This indicates that contrary to the situation for the He-like satellite lines (Parkinson, 1971b, 1972; Gabriel, 1972) the Fe XVI lines observed in the solar corona may be populated more by direct excitation than dielectronic recombination.

4. Conclusions and Future Work

It has been shown above that when the Fe XVII lines, between 13 and 18 Å, are correctly identified in a high resolution X-ray spectrum, the relative intensities are in good agreement with the calculations of Loulergue and Nussbaumer (1973). These calculations take account of population by cascade processes from higher levels. It has been demonstrated that the previous lower resolution observations must be used with great care, particularly in regions of the spectrum where lines are blended together. It has been suggested that several Fe XVI lines of the form $2p^6\cdot nl-2p^5\,3\binom{d}{s}\cdot nl, n\geqq 3$ have been observed in this part of the spectrum.

Now that the problem of understanding the strengths of the Fe XVII lines is resolved an attempt can be made to deduce the abundance of iron from X-ray spectra. It is hoped that the calculations can be extended to the $2p^6-2p^5\,4s$ lines near 12 Å and also to the Ne-I like Ni XIX lines, although the abundance of nickel, being an order of magnitude less than iron, makes most of the lines very weak.

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