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NEW SPECTRA OF THE IRON TRANSITION ELEMENTS OF ASTROPHYSICAL INTEREST

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1964

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NEW SPECTRA OF THE IRON TRANSITION ELEMENTS OF ASTROPHYSICAL INTEREST

by

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A.H. GABRIEL

(Submitted for publication in Astrophysical Journal)

A B S T R A C T

A group of intense lines between 170 Å and 220 Å has been observed in the ZETA discharge, and found to coincide with intense unidentified lines previously observed in the solar spectrum. Using high-current and high-voltage sparks, these lines have again been produced and shown to be due to iron. Similar groups of lines have been produced and measured from each of the elements from calcium to nickel. Over 300 new lines are listed in the wavelength range 400 Å to 100 Å. Two possible mechanisms for the production of these lines are considered.

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Berks.

August 1964. (C/18 JG)

<u>CONTENTS</u>

1. INTRODUCTION

Spectroscopic measurements of high temperature plasmas in the grazing incidence region have now been made by several workers. Heroux (1963) measured the relative intensities of NV lines from the ZETA spectrum, in order to determine the electron temperature. The identification of new spectra from plasmas has been carried out by Fawcett et al (1964) and House and Sawyer (1964). Much of this work is concerned with inert gas spectra, and the classification produced should prove valuable in analysing astrophysical spectra as these become available.

A prominent feature of the ZETA spectrum in this region has already been reported briefly, (Fawcett et al, 1963, Fawcett et al, 1964), and it is the purpose of this paper to examine this problem more fully. This is the strong group of lines between 170 Å and 220 Å. The identification of this system has been considered important for two reasons. First, it appears both in the spectra of ZETA and the sun; and secondly, the intensity in both sources is such that it is the dominant feature in the region 50 Å to 500 Å. It is the purpose of this paper to describe an experimental investigation of these lines in an attempt to classify them, and to report other detailed experimental data that has resulted from these studies. The spectroscopic instruments used have been described elsewhere (Fawcett et al, 1964, Gabriel et al, 1964).

2. THE ZETA EXPERIMENTS

The spectrum of ZETA (Butt et al, 1958) has now been studied using grazing incidence techniques down to 16 Å. For most of this work the discharge was operated in deuterium or hydrogen at a pressure of 0.5 mTorr, sometimes with a small admixture of other gases. The intense system of lines between 170 Å and 220 Å consist of about 8 strong lines and 20 or 30 weaker ones. The absolute intensities have not been measured, but can be estimated both by comparison with lines from known amounts of oxygen impurity, and from the estimated spectrograph sensitivity. Both methods give a brightness for the strongest lines at 171 Å of 3×10^{15} photons/cm^2/sec/sterad, but this can only be considered to be reliable to within a factor of 10.

The astrophysical importance of these lines becomes clear when they are compared with spectra from the sun obtained from rocket or satellite flights. Fig.1 shows a comparison between (a) a solar spectrum taken by Tousey et al (1962), and (b) a ZETA spectrum. It is clear that with a few exceptions, the lines from the two sources correspond. A more striking comparison is possible when the actual wavelengths are examined. The stronger

ZETA lines have been measured in their fourth and fifth order using first order neon reference lines (Fawcett, et al, 1961, Phillips and Parker, 1941, Paul and Polster, 1941) while the weaker members have been measured in their first order against oxygen standards (Edlén, 1934). The solar lines have also been observed by Behring et al (1962) and Hinteregger (1963) and a list has been compiled by Allen and Jordan (1964) from both published and circulated data. This list is printed alongside the ZETA wavelengths in Table 1. It is clear that the wavelengths agree within the errors of measurement.

Some further information can be derived from the production of these lines in ZETA. The addition of controlled amounts of each of the various known gaseous impurities produced variations in the intensity of this system, usually in the form of an increase. However the observed intensity changes were such as to exclude any of these impurities as the element responsible for the lines. Furthermore, the lines were still present when the discharge was operated in a mixture of neon and argon with no hydrogen present.

Photoelectric studies of these lines showed that their peak intensity was reached at about the time of peak current, and that the intensity transient had a duration of about 1 msec. The actual peak intensity increased with increasing current and with decreasing stabilising magnetic field.

The liner of ZETA is made of stainless steel, and this is a further source of impurities, whose presence have been detected in the spectrum. Thus lines from FeI, FeII, FeVIII, FeIX, FeX, FeXI and CrXV have been identified. The intensity of the known iron lines were found to vary with added gaseous impurities in the same way as these new lines.

The above results, in conjunction with the high concentration of iron in the sun, clearly suggest that iron is the element responsible for these new lines. To verify this it was necessary to try to produce them in some source other than ZETA, to which iron may be added or completely excluded.

3. THETA-PINCH EXPERIMENTS

A small theta-pinch was used for a number of studies. Its capacitor bank had an energy of 5 KJ at 10 kV and was discharged through a single turn coil 10 cm. long and 5 cm. diameter surrounding a transparent quartz tube. The discharge was viewed axially.

Iron was successfully introduced into the discharge by adding about 5% of iron carbonyl vapour to the normal filling of 100 mTorr hydrogen. This at once produced the stronger members of the system of lines at 170 Å, as well as other known lines of iron.

This in itself was not conclusive proof that the lines are due to iron, since lines of say Oxygen III are enhanced when iron carbonyl is added and the discharge thereby cooled. Furthermore, quantitative studies were hampered by the deleterious effect of the iron carbonyl upon vacuum gauges and pumps. By observing both these lines and the Carbon VI Lyman α line at 33.73 Å it was possible to state that the line produced at 182.16 is not the Balmer α line of Carbon VI as has previously been suggested. The line at 182.16 is not seriously affected when the discharge is cooled so that Carbon VI no longer appears.

4. SPARK EXPERIMENTS

Attempts were then made to simulate conditions in ZETA, by introducing iron into the theta-pinch from the solid form. At first configurations were chosen which would least disturb the theta-pinch; e.g. a rod down the axis, or a small circular plate at one end of the coil. These were relatively unsuccessful, due to the very small quantities of iron injected. The arrangement which was later found to be most successful produces a high-current iron spark in the discharge chamber, thus injecting large quantities of iron. The disturbance to the normal theta-pinch is severe, and it is doubtful whether the latter is in fact present at all. The geometry is shown in Fig.2. The arrangements shown in Fig.2(a) was that used for iron, the entire insert being made from iron. It is simply a single turn secondary which couples with the external coil, presumably producing a current of the same order as that in the coil, i.e. 0.5 Mamp. A break is provided in the secondary consisting of points touching or almost touching in order to produce the arc. The strap is so shaped that this arc is brought away from the walls of the tube, which is otherwise fractured, and the arc source then occurs on or near the axis of the tube. The arrangement shown in Fig.2(b) is suitable for materials such as chromium and vanadiam which cannot be manipulated like iron. They are introduced in the form of sintered rods into a copper support ring.

As stated above, this source, which will be referred to as a C- strap was very efficient in producing the lines at 170 Å. By using a very short slit in the spectrograph it could be demonstrated that all the lines were emitted from a small region at the arc points. The wavelengths and intensities of the lines are listed in Table 1, alongside those of ZETA and the Sun showing clearly that the stronger lines correspond in all three sources. The spectrum is shown in Fig.1(c). None of these lines were produced without the C-strap present or with C-straps of different materials, thus proving that iron is the element responsible for the lines. In fact, the C-strap source appears to be a very selective means of producing the metallic spectrum, the strong lines of oxygen and carbon being almost absent. For some reason which is not fully understood, the C - strap source fails to emit efficiently when the tube is evacuated instead of being filled with the usual 100 mTorr of hydrogen. This is presumably associated with the initial break-down process in the spark.

Using the C - strap source, grazing incidence spectra were recorded from all the elements from Calcium to Nickel in Z-number order. As with iron, each produced in addition to its reported spectrum, a close group of some 30 or 40 intense lines which were very prominent. The position of the group is such that its wave number tends to vary with Z as proportional to (Z-13), although correlation of individual lines within the group is more difficult. With the exception of calcium and scandium, none of the lines have been reported previously. The wavelengths and intensities of these new lines are given in Tables 2 to 8. The wavelength accuracy varies somewhat with the element, but should always be better than ± 0.05 Å. In the case of calcium and scandium, the wavelengths have been reported and some of the lines classified (Beckman, 1937, Tsien, 1939). Many of the intense lines, however, are among those not classified. As a result of this study, lines in the ZETA spectrum at 202.81 Å , 205.02 Å and 205.69 Å can now be clearly attributed to chromium. This is indicated in Table 1. The relative intensities used in all the tables are obtained from microphotometer tracings of the spectra, and should not be used as quantitative data.

A 70 kV vacuum spark. based upon the apparatus described by Edlén (1934) has been constructed and this was next used for the production of these lines. With an iron anode and carbon cathode spectra up to FeXVI were produced. The system at 170 Å was present weakly and partly obscured by other lines. The spark was cooled in stages by successively adding inductance to the circuit and finally by adding hydrogen to the spark chamber. By this means it is usually possible to group lines according to their degree of ionisation. Unfortunately, a complex spectrum such as iron also shows a strong dependence on excitation energy, so that the separation is not so clear. On cooling the spark, the unknown lines increased in intensity and then faded, while at the same time the changes in other known lines of many of the iron ions were observed. It was thus possible to separate the group of unknown lines approximately into categories with increasing energy required for production. Furthermore, it can be stated that if the unknown lines are normal resonance lines from Fe ions then they must lie mainly between FeIX and FeXIII. This procedure was repeated for Titanium, Vanadium, Chromium and Manganese. The symbol H or L next to some wavelengths in Tables 2 to 6 indicates high or low energy of production respectively, although for the reasons stated above, these should be used with caution.

Using the wavelengths listed in Tables 2 to 8, together with these excitation categories, it is reasonable to try to follow isoelectronic transitions through the sequence. Fig.4 shows a chart produced on the IBM 7030 computer and Benson-Lehner graph-plotter. Each of these groups of lines are plotted on the same vertical scale of wavenumber divided by (Z-13), together with the corresponding groups from Calcium and Scandium. Each spectral line is shown as a short horizontal line whose length is related to its intensity. The Irregular Doublet Law would predict straight horizontal lines joining isoelectronic spectral lines, for transitions between levels having the same principle quantum number, providing the correct screening factor has been chosen (in this case 13). The fact that the group as a whole tends to do so supports the theory that all the lines result from electronic transitions 3d → 3p or 3p → 3s. Some individual lines can be traced through partly by inspection of self-evident patterns and partly by the energy categories of Tables 2 to 8. Thus a higher degree of ionization would be characterised by following a line with a more negative slope, and vice versa, since the screening factor of 13 chosen is only an average value. Some of the more obvious correlations are shown as dotted lines in Fig.4. The usual methods of isoelectronic extrapolation cannot be used to predict the wavelengths. The terms are known only up to Argon or Calcium, and configuration interaction seriously perturbs the levels as far as Scandium.

Edlén (1942) and more recently Rohrlich and Pecker (1963) have identified many visible coronal lines as due to forbidden transitions in the ground configuration FeX to FeXIII. This means that certain intervals within the ground configuration of these ions, either between terms within a multiplet or between different multiplets, are accurately known. It follows that if the new system consists of normal resonance lines of Fe ions, it should contain these intervals as differences of wavenumbers. An attempt has been made to find such intervals. Unfortunately with a wavelength accuracy of only 0.03 Å in most cases, there will always be such intervals within the range of experimental error. Such an attempt is therefore somewhat inconclusive, although there are indications that these intervals are not as common as would be expected.

5. DISCUSSION

The problem is to explain the identity and high intensity of the 8 or 10 strong lines in this group. It is these that present the intensity anomalies in ZETA and the Sun, and in any case, there is no problem in accounting for weak lines of iron in this spectral range. The work described in this paper has now positively confirmed that iron is the element responsible for these lines. Furthermore, similar systems have been produced in the neighbouring elements. It now remains to consider what transitions are responsible. The form of the plot in Fig.4 indicates that a 3d → 3p transition is probably responsible, since the 3p → 3s lines would occur at rather shorter wavelengths, and be less intense. This leaves two possibilities for the type of transition involved.

First there is the normal optical transition of Fe ions in the range FeIX and FeXIII. Since these have the form $3s^2\ 3p^n - 3s^2\ 3p^{n-1}\ 3d$, such transitions would give the strongest resonance lines of these ions. Both initial and final configurations contain several terms, and each of these has several J-split levels so that there is no difficulty in accounting for the number of lines observed. The spark experiments are completely consistent with this interpretation. The high intensity in ZETA is a little difficult to explain on this model, though by no means impossible, and the difficulty of finding the intervals corresponding to known ground term splitting is also a problem.

An alternative model which deserves consideration is that of an inner-shell transition in a low stage of ionization if iron, say FeII to FeIV. This would arise through high energy excitation of low energy ions and would require a high energy plasma in proximity to a cooler iron plasma. This situation might arise both in ZETA and the Sun. The exciting mechanism could be fast electrons, although it is difficult to see why in this case they should discriminate against optical excitation. On the other hand, if photons are responsible, theory predicts most photoionization from the deepest shell attainable, and the cross-sections can become quite high for such processes. The transition would still be 3d → 3p, so that the general form of Fig.4 would be unchanged. However, since the systems in this case can only be truly isoelectronic over a very limited range, attempts to follow individual lines through in Fig.4 would be meaningless. Attempts to find positive experimental support for this model have, however, so far proved unsuccessful.

6. ACKNOWLEDGEMENTS

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Table 1.

Zeta			Sun		Metal Spark (± 0.05Å)	
λ(Å)	Accur. (10^{-2}Å)	Rel. Int.	λ(Å)	Rel. Int.	λ(Å)	Rel. Int.
					IRON:-	
167.52	7	2	167.48	1	167.49	7
168.18	2	3	168.18	1	168.16	8
168.57	2	2	168.53	1	168.54	8
168.82	7	1	168.89	0	168.90	7
171.06	1	11	171.06	10	171.07	9
174.52	2	10	174.48	10	174.54	7
175.26	1	8	175.26	1	175.26	6
177.22	1	8	177.23	9	177.26	8
179.76	2	7			179.76	6
180.41	1	9	180.39	11	180.40	7
182.18	1	6	182.19	2	182.16	5
184.53	1	6	184.53	3	184.50	6
184.80	1	6			184.82	6
185.22	2	6	185.26	1	185.23	8
186.61	2	3			186.61	8
186.86	2	8	186.86	2	186.92	7
188.29	2	8	188.25	6	188.30	4
191.06	5	2	191.20	0		
192.00	5	1				
192.37	5	2	192.37	2		
193.54	5	5	193.43	2		
195.14	5	8	195.03	4		
196.64	5	6	196.73	0	196.74	1
201.11	5	3	201.12	1		
201.72	5	2			201.69	3
202.00	5	2	202.05	2	CHROMIUM:-	
202.81	2	5			202.78	9
203.80	2	9	203.81	1		
205.02	2	3	204.99	2	205.01	7
205.69	5	1			205.65	4
208.66	5	3				
211.30	5	4	211.32	1		
216.69	5	2				
217.07	5	2	217.00	1		
219.10	5	7	219.10	0		
221.85	5	1	221.83	0		

Table 2.

Titanium

λ(Å)	Rel. Int.	Energy	λ(Å)	Rel. Int.	Energy
247.44	6	L	257.48	2	
248.94	4	H	257.71	2	
249.26	3	H	257.86	6	L
249.59	4	H	258.19	3	H
250.03	4	H	258.61	3	H
250.46	8	H	258.91	2	
251.02	7	H	259.26	5	L
252.25	7	H	259.88	3	L
252.62	5	L	261.89	3	H
252.95	9	H	263.27	5	L
254.03	7	H	264.87	3	L
254.72	3	H	265.10	3	L
255.09	5	L	266.02	2	
255.39	7	H	266.56	3	L
255.86	2		267.42	5	L
256.78	4	L	278.11	2	
257.23	2				

Table 3.

Vanadium

λ(Å)	Rel. Int.	Energy	λ(Å)	Rel. Int.	Energy
221.96	2		233.52	7	L
220.20	2		234.19	1	
222.52	3	H	234.83	1	
222.82	3	H	235.72	4	H
223.11	2		236.04	3	H
223.29	2		237.55	3	L
224.50	9	L	239.44	3	L
224.90	3	L	240.26	3	H
225.16	8	L	241.14	2	
225.48	3	L	241.97	2	
225.79	5	L	243.76	1	
227.93	4	L	244.47	1	
228.70	4	H	245.38	1	
229.38	6	L	245.89	2	
230.14	5	H	251.60	2	
230.85	2		251.87	1	
231.85	2		252.12	1	
232.03	3	L	252.40	2	

Table 4.

Chromium

λ(Å)	Rel. Int.	Energy	λ(Å)	Rel. Int.	Energy
200.94	6	L	213.89	4	L
201.15	3	L	215.38	3	L
201.36	3	L	215.76	2	
201.57	6	L	216.06	2	
202.40	5	L	216.67	4	H
202.78	9	L	217.13	3	L
203.02	3	L	217.19	3	H
203.85	4	H	217.55	2	
205.01	7	L	217.61	2	
205.65	4	L	218.06	1	
205.82	1		218.15	1	
206.53	1		219.29	4	
207.07	3	H	219.47	1	
207.44	3	L	219.73	1	
207.61	5	L	219.94	2	
208.63	2		221.41	2	
209.24	2		222.16	2	
209.44	2		222.66	1	
210.16	3	L	223.05	2	
211.42	2		224.38	2	
212.49	2		224.72	1	
212.90	2		225.74	2	
213.05	2		226.20	5	L
213.49	2		226.89	3	L
213.69	2		227.20	4	L

Table 5.

Manganese

λ(Å)	Rel. Int.	Energy	λ(Å)	Rel. Int.	Energy
181.37	3		191.60	7	H
181.88	3		192.09	6	L
182.03	4		192.22	6	L
182.50	7	L	192.42	5	
182.70	6	L	193.43	6	H
182.96	6	L	193.59	5	H
183.15	7	L	194.07	4	H
183.72	6	L	194.34	6	H
184.19	7	L	194.61	6	H
184.54	7	L	194.88	6	L
185.24	5	L	195.07	6	L
185.46	9	L	195.28	5	L
186.35	5	H	195.84	5	L
187.45	5	H	196.38	5	L
187.63	4	H	196.54	5	L
187.76	5	H	197.64	5	L
187.96	5	H	198.23	4	H
188.09	5	L	199.11	8	L
188.19	6	L	199.32	6	L
188.48	9	H	200.67	6	H
188.67	6	H	202.86	9	L
189.06	8	L	204.13	9	L
189.16	8		204.43	6	H
189.49	5	H	205.27	9	H
189.82	4		206.43	3	L
190.73	6	L	206.59	6	L
191.23	4	H	207.98	4	L
191.42	5		208.85	6	L

Table 6.

Iron

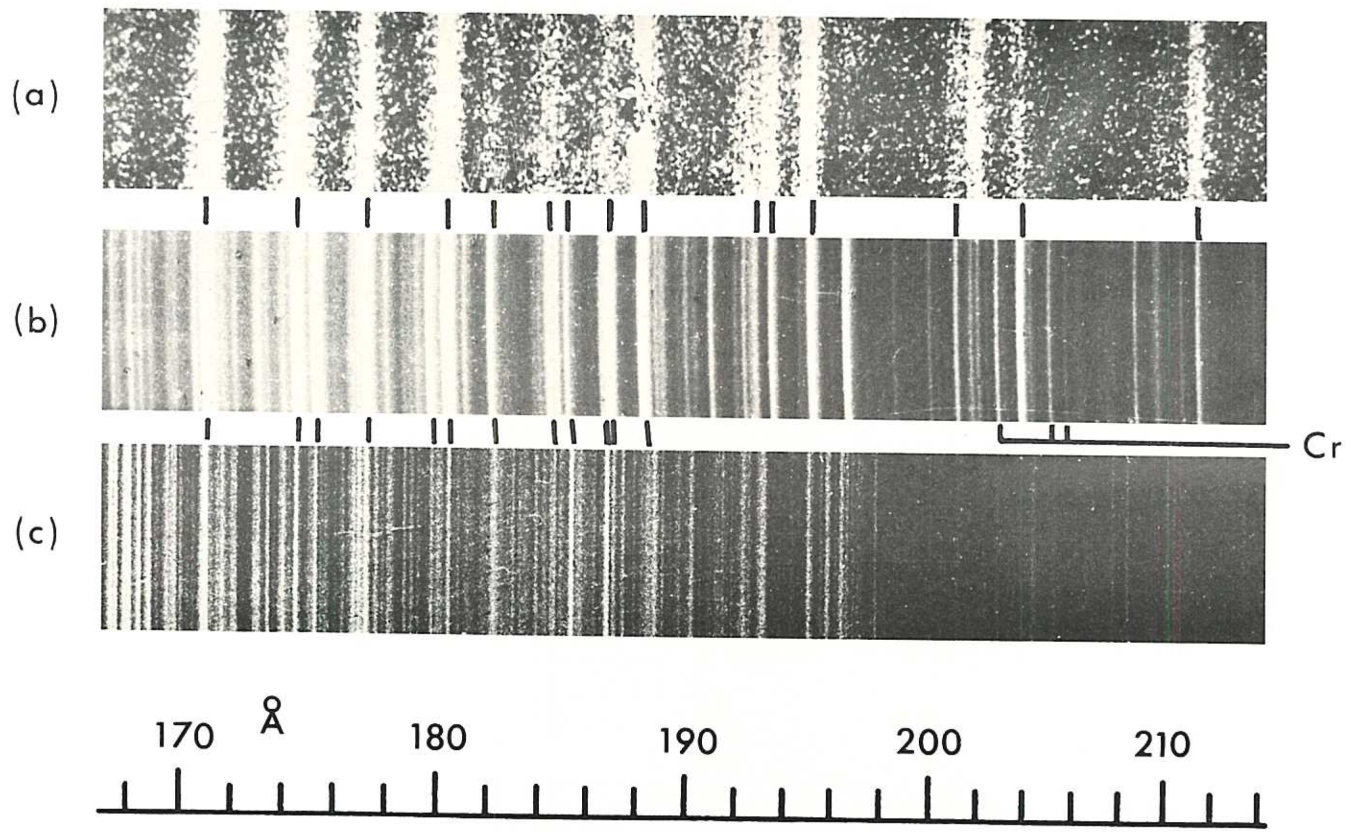
λ(Å)	Rel. Int.	Energy	λ(Å)	Rel. Int.	Energy
165.47	5	L	180.40	7	H
165.95	6	L	182.16	5	
166.35	6	L	182.95	5	L
167.49	7	L	184.50	6	H
167.66	7	L	184.82	6	L
168.00	7	L	185.23	8	
168.54	8	L	186.61	8	L
168.90	7	L	187.27	6	L
169.59	6	L	188.30	4	H
169.88	6	L	188.86	5	H
171.07	9	H,L	189.50	3	H
171.66	3	H	196.74	1	
173.42	6	L	197.44	6	L
174.03	1	H	200.80	1	
174.54	7	H	201.69	3	L
175.26	6	H	202.92	1	
176.32	4	L	203.89	1	
176.74	7	L	204.77	4	L
176.95	7	L	208.44	2	
177.26	8	L,H	209.75	3	
178.15	6	L	210.03	3	
178.71	5	L	210.40	3	
179.00	5	L	210.67	2	
179.23	4	H	216.62	3	
179.76	6	H	217.14	3	

Table 7.
Cobalt

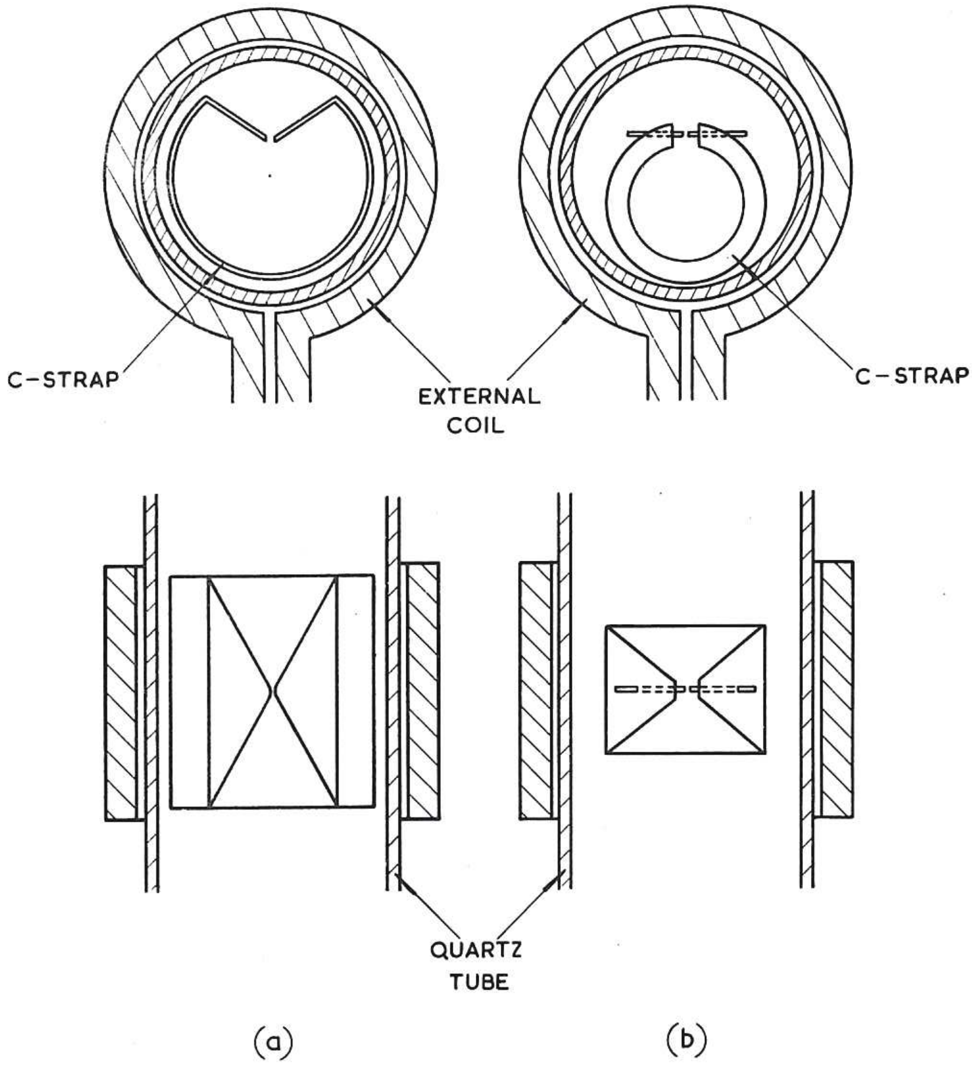
λ(Å)	Rel. Int.	λ(Å)	Rel. Int.	λ(Å)	Rel. Int.
151.91	6	158.80	9	170.69	9
152.50	6	159.55	7	174.67	3
152.66	2	159.95	6	174.71	3
152.96	7	161.46	3	175.93	3
153.27	6	161.70	2	177.30	3
153.76	4	161.88	8	177.93	3
153.89	8	162.07	7	179.08	5
154.90	6	162.32	4	179.16	5
155.08	3	162.57	5	179.75	4
155.27	4	163.85	5	179.96	4
155.49	3	164.91	3	182.17	3
155.63	8	166.09	2	182.39	4
156.59	4	166.71	4		
158.76	7	168.01	5		

Table 8.
Nickel

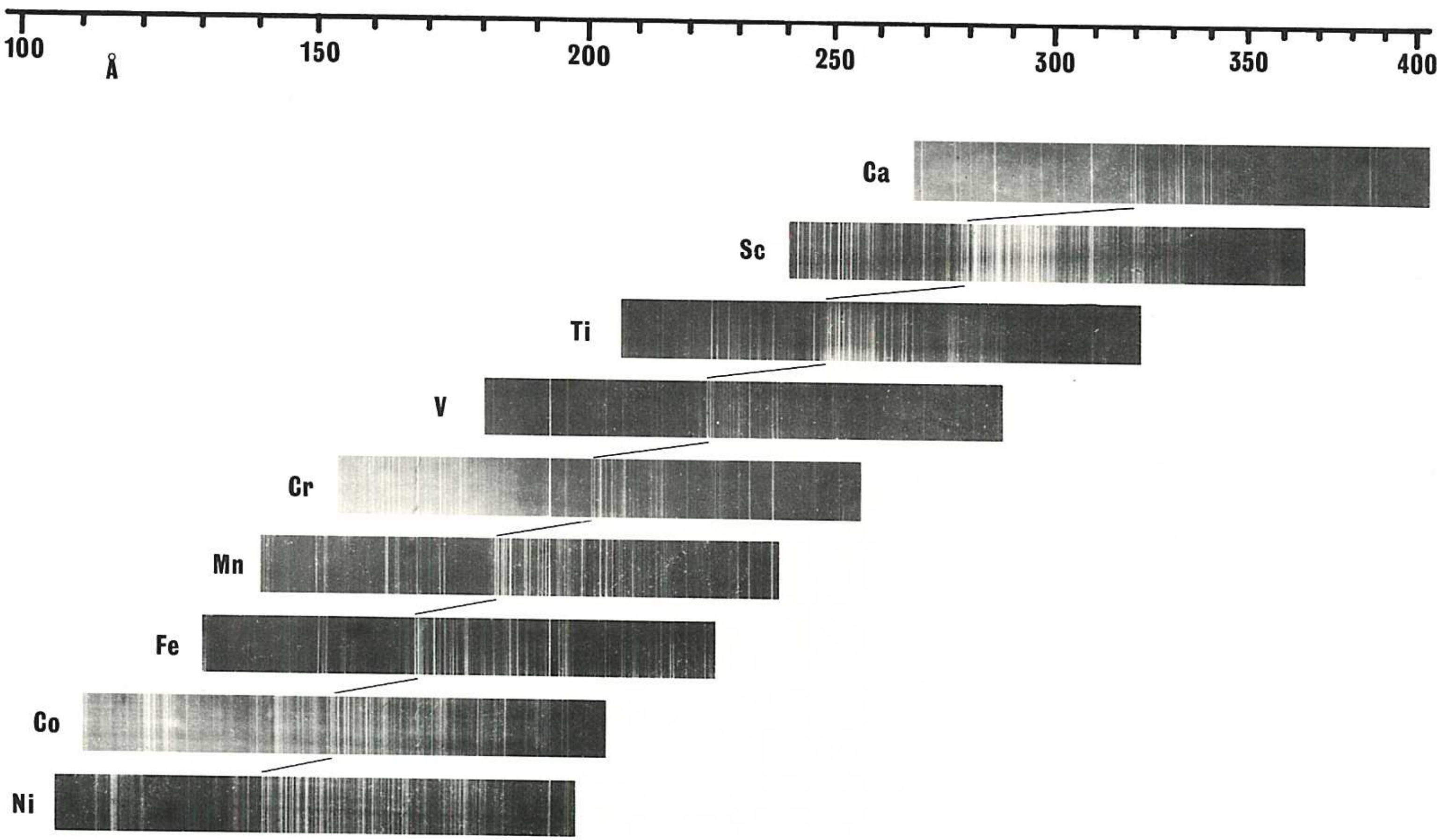
λ(Å)	Rel. Int.	λ(Å)	Rel. Int.	λ(Å)	Rel. Int.
139.55	2	149.47	5	158.37	8
140.04	3	149.97	4	158.54	5
140.52	2	150.29	4	158.75	5
140.83	3	150.56	4	159.97	8
141.06	5	150.82	7	160.16	5
141.35	6	151.01	6	160.38	3
141.70	3	151.25	7	160.60	5
141.87	6	151.48	3	161.51	5
142.00	4	151.70	3	161.94	3
142.22	4	151.85	3	162.16	4
142.42	5	152.14	5	162.90	5
143.80	5	152.31	6	162.61	5
144.22	8	152.68	3	165.43	7
144.99	8	152.95	6	165.69	3
145.73	7	154.15	7	165.81	4
146.08	7	154.93	5	166.08	5
147.00	7	155.62	3	166.29	5
147.15	1	156.30	3	166.46	5
147.27	1	156.68	4	167.37	2
148.37	9	157.24	4	169.60	4
148.62	5	157.56	5		
148.83	4	157.75	4		
149.21	3	158.00	4		



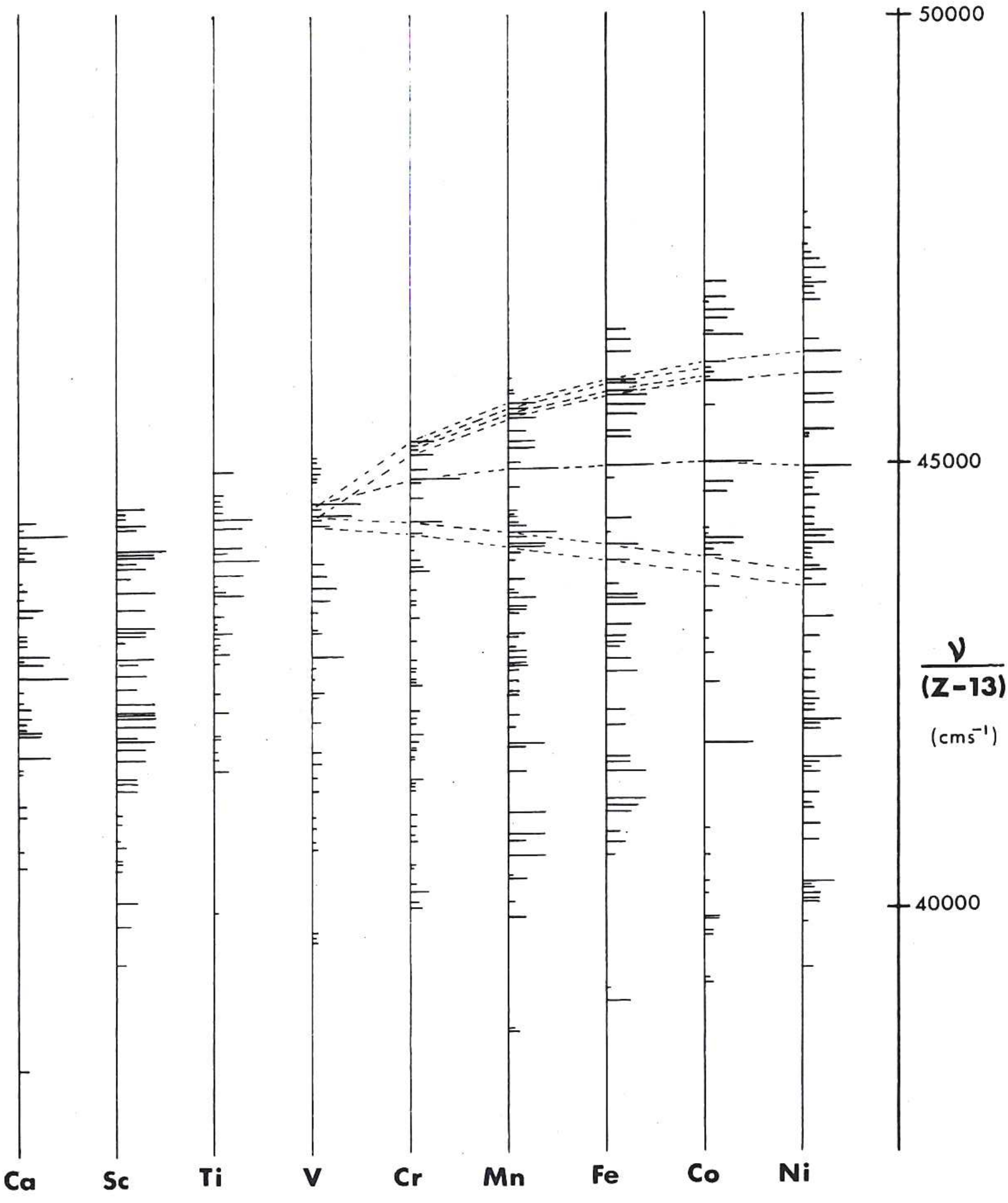
CLM-P 56 Fig. 1
Spectra from (a) the Sun, (b) ZETA and (c) an iron spark, showing the same system of new lines



CLM-P 56 Fig. 2 High-current metal spark



CLM-P 56 Fig. 3
Spectra from high-current metal sparks



CLM - P 56 Fig. 4
Plot of $\nu/(z-13)$ for high-current metal sparks