THE ZETA/SOLAR LINES BETWEEN 170 Å AND 220 Å

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RÉSUMÉ. — *L'identification du système de raies intenses entre* 170 *et* 220 Å *est un problème important de physique solaire. Ces raies ont aussi été observées dans les plasmas à haute température, la machine Zéta et d'autres sources. Ces résultats sont passés en revue et les données permettant d'aboutir à une identification sont discutées.*

ABSTRACT. — *An important problem in solar physics is the identification of the intense system of spectral lines lying between* 170 Å *and* 220 Å. *These lines have also been observed in the high temperature plasma, Zeta, and also in a number of other sources. These sources are reviewed and the experimental evidence relating to the problem of identification is discussed.*

Резюме. — Отождествление системы интенсивных линий между 170 и 220 Å является важной проблемой солнечной физики. Эти линии были также наблюдены в плазмах с высокой температурой, машине Зета и других источниках. Эти результаты просмотрены а данные позволяющие привести к отождествлению обсуждены.

One of the most interesting problems involved in the interpretation of the solar XUV spectrum is the nature and identity of the intense group of lines between 170-220 Å. This is shown by the fact that several speakers have already discussed this problem at this Symposium, and although the main aim of this talk is to present some of the recent experimental work carried out at Culham, it is appropriate to briefly review the whole subject, including some of the points made by previous speakers. The sources to be discussed, i.e. those in which the Zeta/solar lines have been observed are listed in Table I together with the characteristics of the lines and the main conclusions of the particular experiments.

Observations of these lines in the solar spectrum have been carried out by a number of workers. Photoelectric observations have been made by HINTEREGGER and his colleagues [1, 2] and by BEHRING *et al* [3], and photographic observations have been made by TOUSEY and his colleagues [4, 5] The lines were the dominant feature in this region of the spectrum and could not be identified.

In 1963 spectroscopic observations of the high current toroidal discharge, Zeta, were carried out by FAWCETT *et al.* [6] between 16-400 Å using grazing incidence spectrometers. These revealed a group of intense lines between 170-220 Å which were established as being the same system as observed in the Sun. Again no identification was possible, but photo-electric observations of the variation of intensity with time led the authors to conclude that the element responsible was injected into the plasma during the discharge from the walls of the chamber. Since the liner of Zeta is made of stainless steel, the probable indication was that Fe was responsible.

Since then laboratory investigations have been carried out by ELTON *et al.* [7] at N. R. L., Washington, by HOUSE and his colleagues [8] at Los Alamos, and the experiments at Culham have been considerably advanced by FAWCETT and GABRIEL [9]. The experiments by ELTON *et al.* and HOUSE *et al.* both involved the introduction of Fe into high current Thetatron plasmas. This caused the appearance of a number of the unknown lines, but unlike the Sun and Zeta they were not the strongest lines in the region. A similar experiment was carried out initially by FAWCETT and GABRIEL with the same general result. This work confirms that Fe is the source element.

At this point a number of experiments were carried out by FAWCETT and GABRIEL [9]. The relative faintness of the lines in the Thetatron plasma when Fe was added was puzzling, and also limited the extent to which detailed investigations could be carried out. The different means by which Fe entered the Thetatron and Zeta plasmas was therefore considered. In the case of the Thetatron it was introduced by adding 5 % of iron

https://doi.org/10.1017/S0074180900179483 Published online by Cambridge University Press

TABLE I

SOURCES IN WHICH THE ZETA/SOLAR LINES HAVE BEEN OBSERVED

SOURCE	REFERENCES	CHARACTERISTICS	REMARKS
Sun	[1, 2, 3, 4, 5]	Dominant	Unidentified.
Zeta	[6]	Dominant	Material injected from stainless steel liner-probably Fe.
Thetatron Plasma + Fe	[7, 8, 9]	Not Dominant	Confirms Fe as source element.
C-strap Thetatron	[9]	Dominant	System produced in neighbouring elements Ca-Cu inclusive. $3p$ — $3d$ transition deduced.
Vacuum Spark	[9]	Not Dominant	Intensity correlated with known Fe lines between Fe IX and Fe XIII.

carbonyl vapour to the normal filling of 100 m torr hydrogen. In the case of Zeta the work of ROBSON and HANCOX [10] indicates that unipolar arcs are the probable mechanism for injection of Fe into the plasma from the stainless steel liner. These are formed because of the potential difference between the hot plasma and the wall, and form a copious source of metal vapour -- about 10^{17} to 10^{18} atoms are evaporated per Coulomb passed by the arc. This led FAWCETT and GABRIEL to a series of tests which culminated in the C-strap Thetatron source, in which an iron strap, in the rough shape of a C, was placed inside the Thetatron. This allowed an arc to form across the break, and resulted in a spectrum in which the Zeta/solar lines were once again intense, and a dominant feature of the spectrum.

By constructing the C-strap with different materials it was possible to investigate the spectra of the neighbouring transition elements, and a similar line system to that produced by Fe was obtained for the elements from Ca to Cu inclusive. Analysis of the measured wavelengths for each element showed that the wave number varies linearly with Z and is proportional to (Z — 13). From the type of arguement described by EDLÉN [11] this indicates a system in which $\Delta n = 0$, and FAWCETT and GABRIEL then concluded that the transition responsible is $3p$-$3d$.

FAWCETT and GABRIEL also observed these lines in a 70 kV vacuum spark with an Fe anode and a carbon cathode. The Zeta/solar lines were not a dominant part of the spectrum, but known lines of Fe were produced up to Fe XVI. By varying the excitation conditions in the spark the intensities of the unknown lines were compared with the known Fe lines and showed a correlation with ions in the range Fe IX-Fe XIII. Observations of the intensity variation of these lines with solar activity, made from the OSO Satellite, were reported earlier by NEUPERT [12], and also indicated a correlation with the intermediate stages of ionization of Fe.

Since the resonance lines of such ions are formed by $3p$-$3d$ transitions, the existing evidence strongly suggests that the Zeta/solar lines are the resonance lines of intermediate stages of ionization of Fe. This is further backed up by the theoretical work of Miss JORDAN [13] who by isolectronic extrapolation calculated the wavelengths of the transition $3p^n$ — $3p^{n-1}\ 3d$ in the ions Fe IX to Fe XIV and obtained the following values :

Fe IX	$3p^6\ {}^1S_0$	— $3p^5\ 3d \left[\frac{1}{2}\right]_1^0$	222 Å
Fe X	$3p^5\ {}^2P^0_{8/2}$	— $3p^4\ 3d\ {}^2D_{5/2}$	211 Å
Fe XI	$3p^4\ {}^3P_2$	— $3p^3\ 3d\ {}^3D^0_3$	216 Å
Fe XII	$3p^3\ {}^4S^0_{3/2}$	— $3p^2\ 3d\ {}^4P_{5/2}$	186 Å
Fe XIII	$3p^2\ {}^3P_2$	— $3p\ \ 3d\ {}^3D_3$	188 Å
Fe XIV	$3p\ \ {}^2P^0_{3/2}$	— $3d\ \ {}^2D_{5/2}$	219 Å

Miss JORDAN estimates a wavelength accuracy of about 10 Å in these calculations. The grouping of these lines in the region of the observed Zeta/solar lines is due to a wavelength reversal in the extrapolation of the type discussed by EDLÉN [11].

It is apparent that the past year has seen considerable advances towards a solution to the problem of identification of the Zeta/solar lines, but

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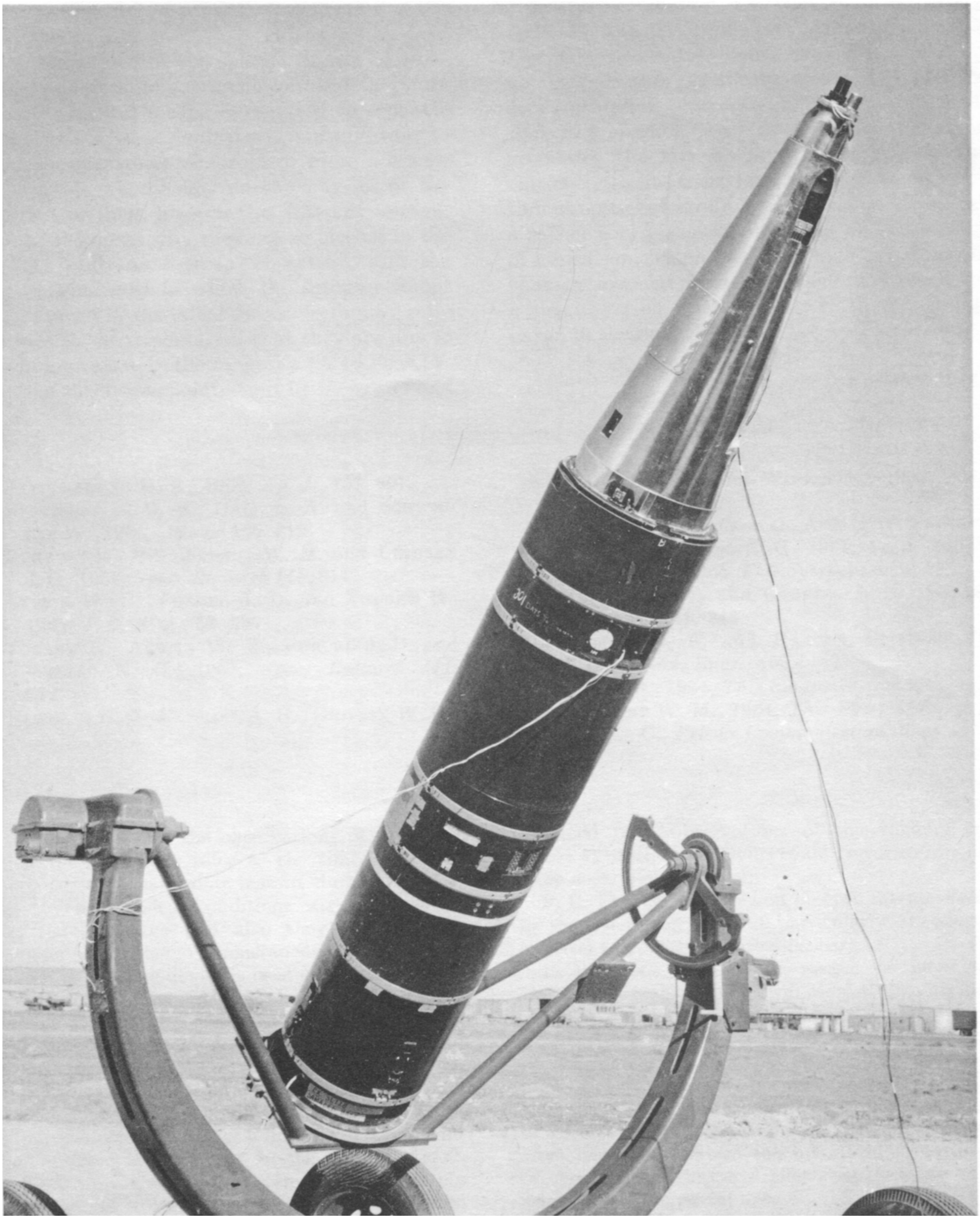

Pl. 1 — First launching of the British stabilized Skylark Rocket by R. Wilson.

an essential requirement for a further advance is the accurate measurement and classification of the spectra of Fe IX to Fe XIV. This is not an easy problem since the different spectra cannot be separated by isolectronic extrapolation and therefore some experimental means is required to separate the various stages of ionization. In addition to this purely spectroscopic problem some advance may be made by considering the physics of the production of these lines in the different sources. It is not yet known why they are so intense in the Sun, Zeta and the C-strap Thetatron, and the rather unusual way in which the source element Fe is produced in the latter two sources may raise difficulties to the explanation that they are due to stages of ionization in the range Fe IX to Fe XIV. Because of this it was pointed out by FAWCETT and GABRIEL that it may be necessary to consider a different explanation, i.e. that they are internal $3p$ — $3d$ transitions in lower stages of ionization. The experimental evidence reviewed above does not exclude this possibility, but it may be necessary to think in terms of a different plasma model, since any electron temperature which abundantly populates the low stages of ionization will not efficiently excite these lines which have an excitation potentiel of about 70 eV. A possible model is a rather cool plasma, containing Fe in low stages of ionization, which has some high excitation mechanism associated with it which may result from a neighbouring hot plasma. Such a possibility exists in the Sun, Zeta and C-strap Thetatron.

Manuscrit reçu le 2 *octobre* 1964.

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Discussion

L. GRATTON. — Do the observations of the spectrum in the Thetatron refer to the time-integrated discharge or to a particular instant during this discharge ? The physical conditions vary very much during the discharge and also they may depend very much on other circumstances, for instance, whether a preionizing device is used or not ?

R. WILSON. — The spectrograms obtained of the Thetatron with Fe added and the C-strap Thetatron are all time-integrated. As you say, the physical conditions vary during the discharge and the spectrum is therefore transient in character ; further, the physical conditions will depend on a number of controllable parameters such as gas density, gas current, method of preionization etc. In the case of the C-strap Thetatron, the whole system was deliberately designed so as to optimize the strength of the Zeta/solar lines and the use to which these results were put, *i. e.* a wavelength analysis for the transition elements, is not affected in any way by these variable characteristics. The correlation between the strength of the Zeta/solar lines with known lines of Fe was obtained from observations of the vacuum spark whose excitation conditions could be varied in a much more controllable fashion.

P. C. FISHER. — Can you observe intense Fe lines in the Thetatron without particularly affecting the electron temperature in the discharge ?

R. WILSON. — No. Any means of introducing Fe or other trace element will almost certainly affect the electron temperature. Thus the actual appearance of new lines on the introduction of Fe is not in itself a conclusive proof that these are due to Fe since lines of other elements appeared due to the change in electron temperature. However, the introduction of several of the transition elements in the work I have described enables the unambiguous separation of chemical and physical effects as the cause of the appearance of spectral lines.

Mrs E. v. P. SMITH. — What limits your wavelength range to 210 Å at the long wavelength ? In the solar ultra-violet, of course, we see other lines at longer wavelengths. In particular, there are the lines attributed to Fe XIV, two of which are thought

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