SOME PROBLEMS RELATING TO SOLAR LINE IDENTIFICATION

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Abstract. A review is given of some of the problems of classification and intensity analysis involving unidentified or recently identified lines in the ultraviolet solar spectrum. In particular, attention is drawn to the present position regarding two and three electron spectra in the soft X-ray region, and forbidden transitions within the ground configurations at longer wavelengths.

1. Introduction

Identification of observed spectra is normally a first step towards interpretation of the measured intensities of the lines. In addition to any contribution to fundamental atomic physics, such interpretation can yield information on the temperature/density structure of the solar atmosphere, as well as on the abundances of elements, dynamic processes and heating mechanisms.

Most of the more intense lines observed in the solar spectrum between 1.5 Å and 2000 Å have now been identified. In spite of this, there are a number of interesting problems surrounding the unidentified or recently identified lines. When the excitation mechanism departs significantly from LTE, as it does throughout the chromosphere and corona, it is of particular value to study those lines whose intensities are determined by more complex factors. These include forbidden and intersystem lines as well as transitions from autoionizing levels. The identification of such lines is therefore of considerable importance.

This paper will not attempt to review all the outstanding identification problems, but rather to select a few areas of particular interest involving unidentified or recently identified spectra. In many cases, these are illustrated by drawing on current work at the Astrophysics Research Unit. It is convenient to subdivide the lines considered in terms of the quantum numbers of the jumping electron.

2. Transitions 2→1

These transitions occur in hydrogen-like and helium-like ions, as well as through inner-shell transitions in lower stages of ionization. Recent problems are illustrated by the schematic spectra in Figure 1. This shows the appearance of spectra in the region of the helium-like O VII lines as observed in (a) laboratory sources, sparks, etc. and (b) from the Sun. On the long-wavelength side of the resonance line, $1s^2\ {}^1S$–$1s\,2p\ {}^1P$, and intercombination line, $1s^2\ {}^1S$–$1s\,2p\ {}^3P$, additional lines are seen. In laboratory plasmas these appear as several lines of low intensity; in the Sun as a single intense line. At first, both these groups of features were thought to be of similar

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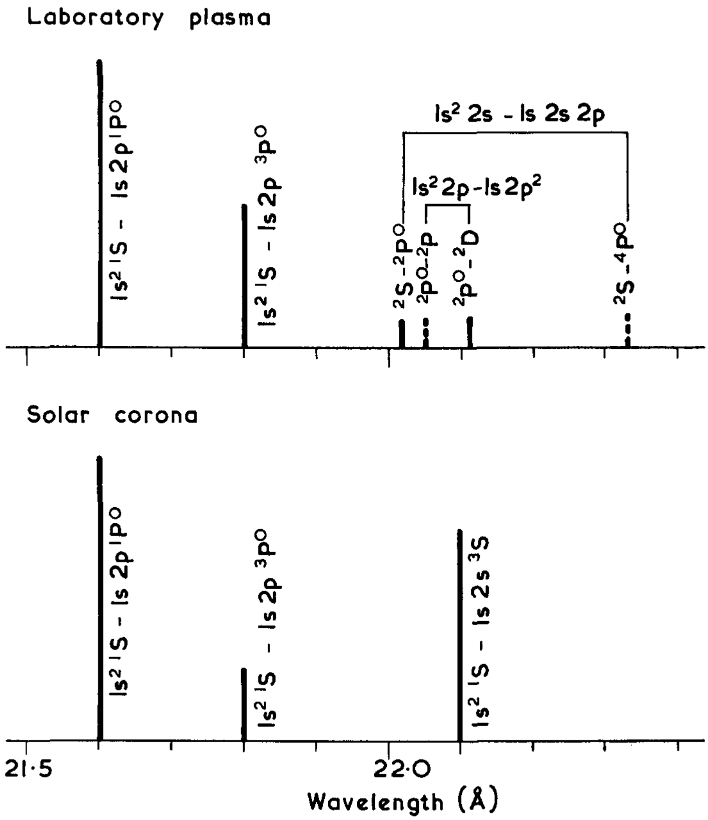

Fig. 1. Schematic representation of spectra observed in the vicinity of the O VII resonance line.

origin. However, the lines have now been classified (Gabriel and Jordan, 1969a) and shown to arise from different types of transitions.

2.1. DIELECTRONIC SATELLITES

The lines observed in laboratory plasmas are due to inner-shell transitions in lithium-like ions, of the type $1s^2\,2s$–$1s\,2s\,2p$ or $1s^2\,2p$–$1s\,2p^2$. In all but very high density plasmas, the initial states are autoionizing levels, and are formed from the helium-like ion by dielectronic recombination. Their intensity relative to the helium-like resonance line is independent of electron density N_e but scales with the electron temperature as T_e^{-1} and with the ionic charge as Z^4 (if T_e is assumed to scale as Z^2). In typical conditions, this relative intensity might be approximately 0.01 for oxygen, 0.1 for silicon, 0.3 for calcium and 1 for iron. Such lines would not therefore be observed from oxygen in the solar spectra where the recording sensitivity for weak lines has so far been much less than in laboratory experiments but they would be expected from heavier elements, and have been reported (Neupert and Swartz, 1970) in iron in roughly the ratios predicted by theory. The present theory (Gabriel *et al.*, 1969) should be valid up to oxygen and has been confirmed by laboratory experiments. For higher ions, a more complete theory will be required. The relative intensities will then serve to measure T_e in active regions.

2.2. HELIUM-LIKE FORBIDDEN LINES

The intense solar line in Figure 1 is due to the $1s^2\ {}^1S$–$1s\ 2s\ {}^3S$ forbidden line in O VII. The transition has also been seen in other ions from C V up to Ca XIX and possibly Fe XXV. The classification of these lines in the solar spectrum has shown that the $1s\ 2s\ {}^3S$ level decays primarily by single-photon magnetic dipole emission and not by two-photon emission as previously expected. Following this, the transition probabilities calculated by Griem (1969) have been used to derive a theory for the relative intensities as a function of N_e (Gabriel and Jordan, 1969b). It has now become clear that there is an error in the Z scaling of Griem's transition probabilities, and the theory has been recalculated with semi-empirical values for the forbidden line transition probability (Freeman *et al.*, 1970; Gabriel and Jordan, 1970). Recently, more precise values have been calculated by Drake (1971), and these are in satisfactory agreement with the semi-empirical values used by Freeman *et al.*

The forbidden line is comparable in intensity with the resonance and intercombination lines and to first order the ratios do not scale with T_e or Z. However, above some critical density N_e^*, intensity is transferred from the forbidden to the intercombination line with increasing N_e, resulting in the extinction of the forbidden line at laboratory plasma densities. The critical density N_e^* scales approximately as Z^{13}. We thus have a means of measuring N_e over certain density ranges which can occur in solar active regions.

For heavier ions it is possible to see in the Sun both the dielectronic satellites and the forbidden line. A good example in silicon is shown in a recent spectrum by Walker and Rugge (1971), reproduced in Figure 2. These authors have identified many of the dielectronic satellites, including some in the two-electron configurations.

3. Transitions $2p \rightarrow 2s$

A number of recent identifications relating both to these transitions and to those of Section 4 have been made from solar spectra by Burton and Ridgeley (1970) and Freeman and Jones (1970) and from laboratory studies (Fawcett *et al.*, 1970; Fawcett, 1970a, b).

$2p \rightarrow 2s$ transitions can occur in ions with ground configurations $1s^2\ 2s^2\ 2p^n$ ($n=0$ to 5) or $1s^2\ 2s$. Allowed transitions of this type in lithium-like and beryllium-like ions are important through their application to the measurement of electron temperatures (Heroux, 1964). Many of these transitions have been measured recently in laboratory sources from sodium to chlorine and several have also been identified in the solar spectrum.

Intersystem lines are of particular value in solar analysis. Since both collisions and radiation compete in depopulating the upper levels, intensities relative to allowed lines will, over certain density ranges, depend on the density. In addition the low

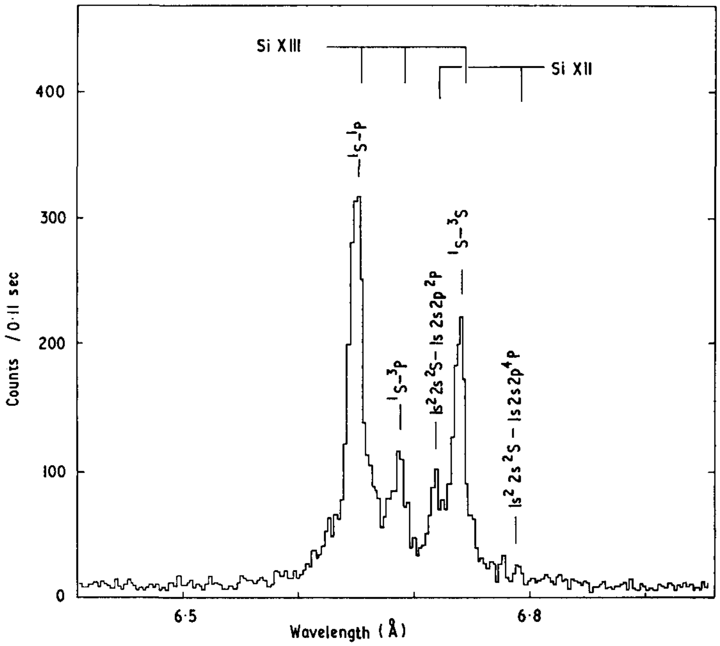

Fig. 2. Solar silicon lines observed in the X-ray region by Walker and Rugge (1971).

f-values makes it entirely safe to assume that such lines are optically thin in emission over a wide range of conditions. Because of this effect, such lines show a large limb brightening and are most readily observed in solar limb spectra. Using this technique, Burton and Ridgeley identify lines from C III, N III and IV, O I, III, IV and V and Si XI.

4. Transitions $3p \rightarrow 3s$

These will be the lowest transitions in ions with configurations from $3s$ to $3s^2\,3p^5$. A large number of lines are possible and it is thought that many of the solar lines in the region 200 Å to 400 Å are due to such transitions in iron. Recent laboratory work on elements between calcium and iron by Fawcett (1970b) has led to classifications of some of the solar lines and has predicted others.

Intersystem lines in these configurations are not well known, only Si I to Si III being identified in the solar spectrum. Further work in this area could be important.

5. Transitions $3d \rightarrow 3p$

These transitions in configurations $3s^2\,3p^6\,3d$ to $3s^2\,3p$ in iron are responsible for the group of very intense lines observed in the solar spectrum between 170 Å and 250 Å. The majority of these are now classified (Gabriel *et al.*, 1966; Fawcett *et al.*, 1967) although a few of the weakest lines remain unidentified.

6. Transitions 3→2

Such transitions can take place in any ions with outer shell $n=2$ electrons. An outstanding problem occurs in the solar spectrum between 9 Å and 18 Å. During solar flares, Neupert *et al.* (1967) in their OSO-III experiment observed greatly enhanced emission from a number of lines throughout this region. These they have tentatively classified, by comparison with calculated spectra, as $2p$–$3s$ and $2p$–$3d$ transitions in Fe XVII to Fe XXIV. With their wavelength resolution limited to 0.05 Å, they are only able to assign transition arrays and not individual terms. Their result is shown in Figure 3. Several of these lines have been produced in the spectrum of a low inductance spark by Feldman and Cohen (1967), but here again the resolution is insufficient to assign term values. Fawcett (1970a) has classified many of these transitions in the isoelectronic sequences from sodium to calcium. His extrapolations confirm Neupert's identifications and indicate probable dominant terms.

The changes in intensity of the solar flare lines as a function of time contain important information on the nature of the flare process. A more complete study of these lines at higher resolution is therefore indicated both in the Sun and in laboratory sources.

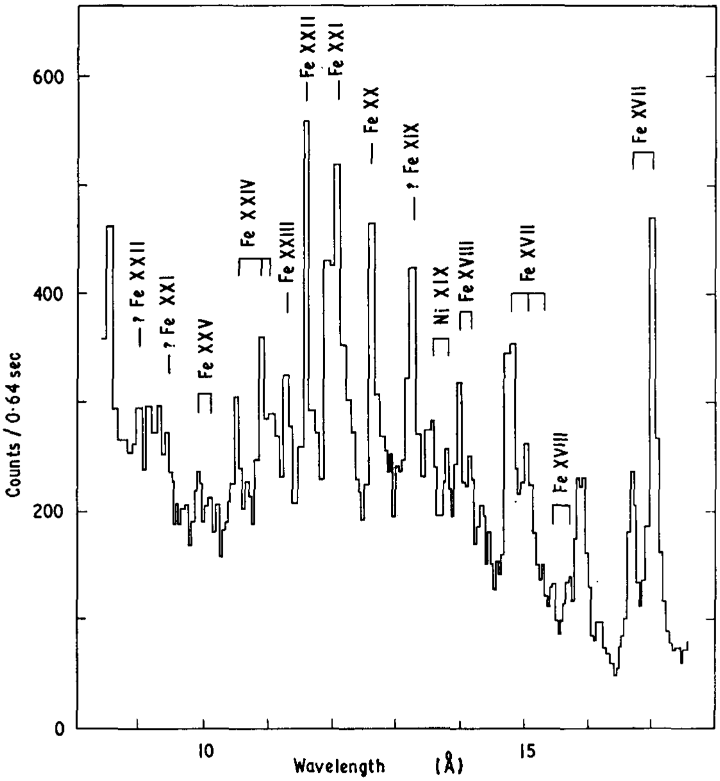

Fig. 3. Iron lines recorded during a solar flare from the OSO-III satellite (Neupert *et al.*, 1967).

7. Transitions Within the Ground Configuration

These transitions occur between terms or levels within the configurations $3p^n$ or $2p^n$ with $n=2$ to 4. They are the forbidden lines which for coronal ions occur at wavelengths from 1000 Å through to the infra-red. Many of those at wavelengths longer than 3000 Å have now been classified, although some of these are tentative and several remain unidentified (Jefferies, 1969). Others lie in the ultraviolet and have only recently become accessible.

One approach to this problem is a detailed study of the shorter wavelength allowed transitions which connect to the ground configuration. Unfortunately a high wavelength accuracy is necessary here to give a moderate accuracy in prediction of the forbidden lines. However, the laboratory experiments described in Section 3 and 4 are now making some contribution to this problem. As an example, the recent classification by Fawcett of the Fe XIII multiplet $3s^2\ 3p^2\ {}^3P$–$3s\ 3p^3\ {}^3S$ gives the splitting of the ground ${}^3P$ term. This provides the first laboratory confirmation of the forbidden solar ${}^3P_0$–${}^3P_1$ and ${}^3P_1$–${}^3P_2$ lines originally classified by Edlén (1942) by isoelectronic extrapolation.

The solar ultraviolet forbidden lines require the observation of isolated regions above the limb, using spectrographs carried in space vehicles. The solar limb spectra of Burton *et al.* (1967) enabled Fe XI and XII lines to be identified in the region 1200 Å–1500 Å. This work can be greatly extended by measurements carried out recently during the total eclipse of 7 March, 1970. In a collaborative experiment between Imperial College London, the Astrophysics Research Unit, Harvard College Observatory and York University Toronto, a series of flash spectra were obtained from a rocket in the region 850 Å to 2100 Å at times throughout second contact (Speer *et al.*, 1970). A frame from this data recorded close to totality, is shown in Figure 4. The chromospheric spectrum has been obscured at this stage, except for prominences, and coronal lines appear as complete rings. Some lines from very high temperature regions show incomplete rings. In Figure 4, the allowed transitions having coronal extensions are indicated. All the other ring images are due to coronal forbidden lines, mainly from the configurations indicated above. Assignments include $3p^n$ configurations in iron and nickel, and $2p^n$ configurations in silicon and sulphur (Gabriel *et al.*, 1971). Confirmation of these is difficult in some cases, and may be assisted by observation of the region 2000 Å–3000 Å, planned for later eclipse flights.

8. The Photospheric Spectrum

This spectrum, which consists principally of absorption lines of neutrals and first ions of the transition elements, is now being extended further into the ultraviolet. The detail is complex and high wavelength resolution is necessary. The earlier work of Tousey (1964) carried these measurements down to 2200 Å. This has now been extended using a rocket-borne echelle instrument designed at Culham. In its first flight (Boland *et al.*, 1971) it obtained a photospheric spectrum down to 2000 Å which

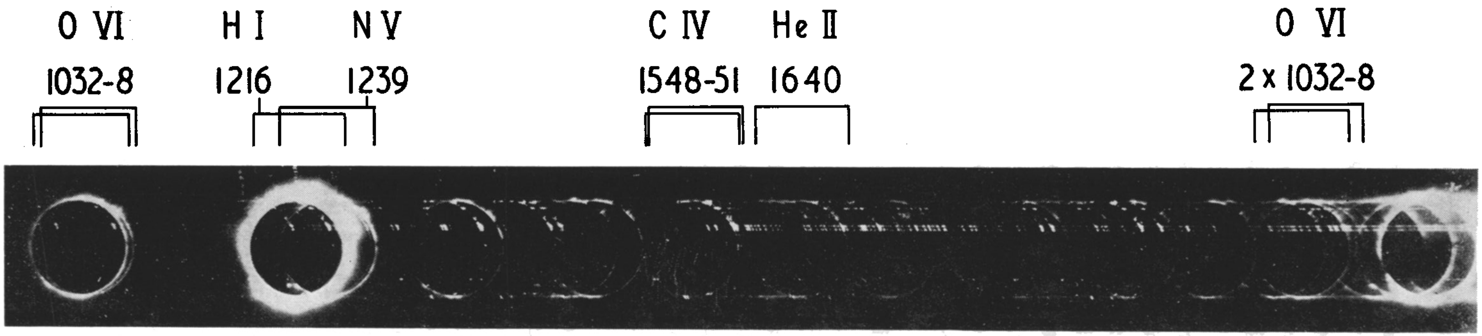

Fig. 4. Slitless coronal spectrum recorded during the eclipse of 7 March, 1970 (Speer *et al.*, 1970). The identifications indicated relate to known permitted transitions. Annular images without identifications marked are due to forbidden transitions.

resulted in the identification of 663 new solar lines in the range 2000 Å to 2200 Å. This spectrum is shown in Figure 5, in the familiar raster pattern resulting from crossed high and low dispersion. A more recent flight of this experiment has resulted in an extension of this spectrum to 1900 Å, and is at present being analysed.

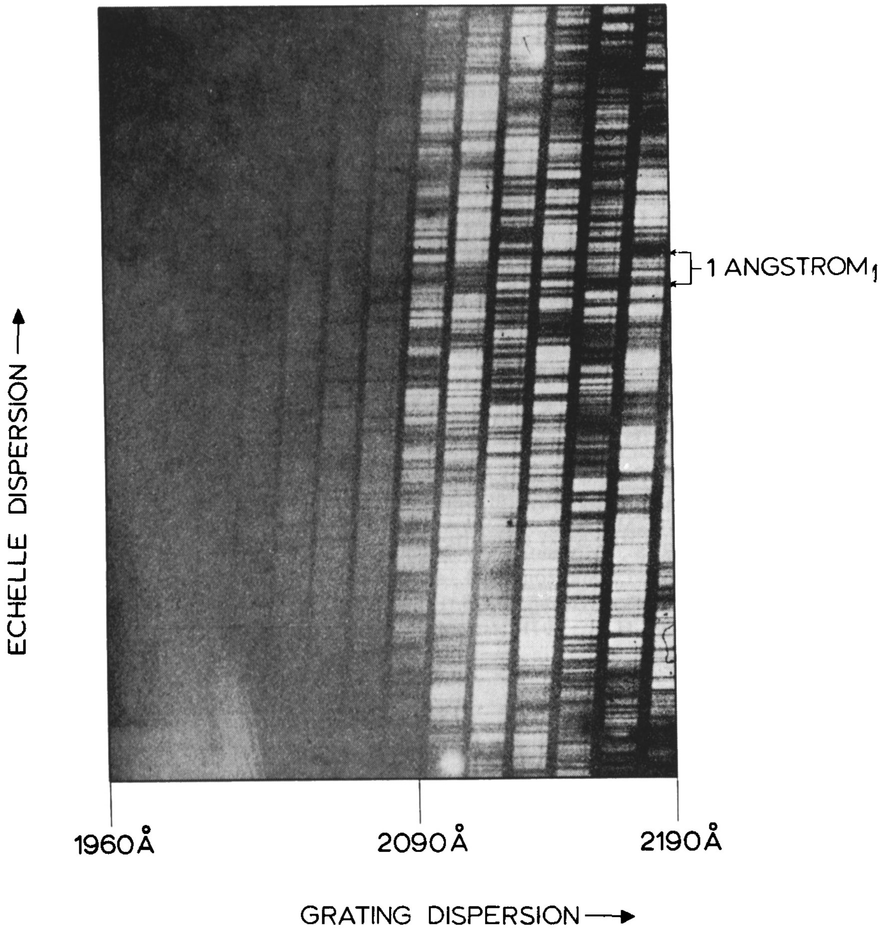

Fig. 5. Photospheric spectrum recorded at high spectral resolution (Boland *et al.*, 1971).

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