SECTION IV

THE SOLAR SOFT X-RAY SPECTRUM

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DIELECTRONIC SATELLITE SPECTRA IN THE SOFT X-RAY REGION

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Abstract. Satellite lines, situated on the long wavelength side of the helium-like ion resonance line, can be observed in highly-ionized ions both in laboratory sources and from the Sun. Although seen for more than 30 years, these lines have only recently been classified in detail as inner-shell transitions in lithium-like ions. Laboratory experiments have shown that under steady-state conditions these satellites are produced by dielectronic recombination, although in transient ionizing plasmas direct inner-shell excitation can be important. Detailed calculations have been carried out for high Z ions up to copper, and the results can be compared with solar flare spectra in iron. Such comparisons allow both the electron temperature and the transient state of the plasma to be determined. Laboratory spectra from such high-Z ions are different in appearance, and may be dominated by processes resulting from the transient ionizing state of the plasma.

1. Introduction

The satellite lines considered in this review are systems of lines that appear on the long-wavelength side of members of the resonance series of highly ionized helium-like and hydrogen-like ions. They have been known for over 30 years in the optical spectra of laboratory sources, notably the high voltage vacuum spark. During the last six years there have been a number of observations of similar features in the spectra from solar flares and active regions.

Edlén and Tyrén (1939) first reported these satellites from a carbon vacuum spark. Their spectrum is shown in the frontispiece, in which the satellite groups marked A, A' and B are shown alongside the normal spectra of C v and vi. They proposed that the transitions were due to the same configurations as the parent line, but with an additional electron in some outer orbit nl throughout. Thus they would be

$$1s^2\,nl - 1s\,2p\,nl$$
$$1s^2\,nl - 1s\,3p\,nl$$
$$1s\ \ nl - 2p\,nl$$

corresponding the groups A, A' and B respectively. The strongest satellites, well separated from the parent line, would have $n=2$ for the extra electron; $n=3$ would lie closer to the parent line, while $n \geqslant 4$ might not be separable from the parent line.

Although there were many and detailed subsequent observations of the satellite lines, further interpretation had to wait until some three years ago to make significant advances. It is now possible in most cases to classify the individual satellites according to the LS terms responsible. The population mechanism of the initial states is known to be principally by dielectronic recombination and this leads to the intensity ratios being temperature dependent, although independent of density. Finally, recent theoretical work has carried this interpretation up to heavy ions such as iron, which are

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observed in solar flares. The theory is more complex for such highly-charged ions, in which the satellite lines become comparable in intensity with the resonance line.

2. Early Work

Following the observations by Edlén and Tyrén (1939), Wu (1940) and later Wu and Shen (1944) attempted to compute the satellite spectra by variational techniques. These proved insufficient to reliably assign term designations to the lines. Later, there were many observations of these satellites in different ions in laboratory plasmas, in particular in the high-temperature plasma devices developed for research into controlled thermonuclear fusion. Roth and Elton (1968) tabulated many satellites due to carbon and oxygen, produced in a large theta-pinch device.

Attention was refocussed on this highherto rather academic problem by the observation of two unusual types of feature in the solar spectrum. The first was the recording of the X-ray spectrum of a solar flare by Neupert *et al.* (1967) from the Orbiting Solar Observatory OSO 3. This showed an extensive intense satellite structure associated with the Fexxv resonance line at 1.85 Å. Their spectrum is shown in Figure 1. The authors suggested that these lines must represent inner-shell $1s$–$2p$ transitions, not

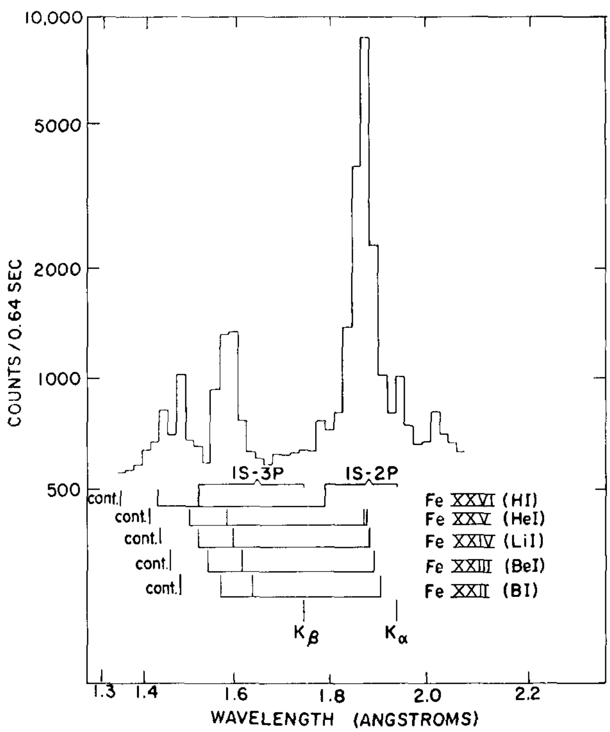

Fig. 1. The iron spectrum near 1.8 Å, obtained during a solar flare from the OSO-3 satellite (Neupert *et al.*, 1967).

only in Fe XXIV but also in Fe XXIII, XXII, etc. The second solar feature was observed by several groups looking at the soft X-ray spectrum from active regions (Fritz *et al.*, 1967; Rugge and Walker, 1968; Jones *et al.*, 1968). They found a single 'satellite' at 22.1 Å on the long-wavelength side of the O VII resonance line. Unlike the laboratory spectra in which such satellites are weak, this feature was comparable in intensity with the resonance line.

These two problems were widely discussed at the second Conference in this series at Maryland in 1967, and were responsible for renewed efforts in the interpretation of the satellites. Subsequently, Gabriel and Jordan (1969a) were able to classify the individual terms in the satellites to helium-like ions, and showed that solar 22.1 Å line was *not* one of these transitions. They proposed that the 22.1 Å line was in fact a hitherto unexpected forbidden transition in O VII due to $1s^2\ ^1S$–$1s\ 2s\ ^3S$, a suggestion that has been subsequently supported by other observations and by theory. This line is thus of totally different origin from the satellites, although it is of historical importance in having stimulated the study of the satellites lines.

Satellites to helium-like ions are much more easily observed than those to hydrogen-like ions. This is a result of the shell structure of the ions, ie the discontinuous way in which the ionization potential increases with successive ionization. The remaining part of this paper will therefore be limited entirely to the consideration of satellites to the helium-like ion resonance line $1s^2$–$1s\ 2p$. Other workers have been concerned with interpretation of the hydrogen-like ion satellites, notably Goldsmith (1969) and Feldman and Cohen (1969) in laboratory plasmas, and Walker and Rugge (1971) from the Sun.

3. Classification of the Terms

The terms responsible were classified by Gabriel and Jordan (1969a) in the elements from carbon to aluminium. Over this range it is possible to work in the LS coupling approximation, ignoring fine structure splitting. The complete range of transitions possible is listed in Table I. Wavelengths were computed for all these transitions using the Froese (1969) Hartree-Fock method with configuration mixing. The mixing was included between the initial states of transitions (a) and (b) and also (g) and (h) in Table I. Calculations were also carried out for the 1–2 transitions of the helium-like

TABLE I

Possible satellite transitions

(a)	$1s^2\ 2s\ ^2S$	$-\ 1s\ 2p\ (^1P)\ 2s$	$^2P^0$	A/I
(b)		$-\ 1s\ 2p\ (^3P)\ 2s$	$^2P^0$	A/I
(c)			$^4P^0$	
(d)	$1s^2\ 2p\ ^2P^0$	$-\ 1s\ 2p^2$	^4P	
(e)			^2P	
(f)			^2D	A/I
(g)			^2S	A/I
(h)		$-\ 1s\ 2s^2$	^2S	A/I

ion. Comparison between experiment and theory was made using the *difference* in energy between the transition energy for each satellite and that of the helium-like ion resonance line. In this way many of the relativisitic corrections and errors in the Hartree-Fock method cancel out, and it was possible to assign classifications to all the satellites observed. These classifications were further supported by considerations of the relative intensities, discussed below.

4. Mechanism and Intensities

It should be noted that all of the initial states listed in Table I lie well above the first ionization potential of the lithium-like ion. However, only those marked A/I have permitted autoionizing transitions in LS coupling. The triplet terms and also the $1s\,2p^2\,{}^2P$ term are non-autoionizing.

With regard to possible mechanisms for producing the satellite initial states, Gabriel and Jordan (1969a) considered firstly the process of dielectronic recombination:

$$1s^2 + \varepsilon p = 1s\,2p\,2s$$
$$1s^2 + \varepsilon d, s = 1s\,2p^2 \quad \text{or} \quad 1s\,2s^2$$

This mechanism excludes the production of non-autoionizing terms. They showed that except in transient high density plasmas, only those transitions marked A/I in Table I were strong. However, for high-density spark plasmas, the other lines appeared, in particular the transition (e). They proposed that under these conditions, an additional mechanism of inner-shell excitation of the lithium-like ion contributed; ie

$$1s^2\,2s + \varepsilon = 1s\,2p\,2s + \varepsilon$$
$$1s^2\,2p + \varepsilon = 1s\,2p^2 + \varepsilon$$

The dielectronic recombination mechanism was further supported by an experimental observation of the time history of the satellite (a) in a transient theta-pinch plasma. This was found to follow the population density of helium-like ions, and not that of the lithium-like ions.

The quantitative theory for intensities produced by dielectronic recombination was first given by Gabriel *et al.* (1969) and in greater detail by Gabriel and Paget (1972). Figure 2 shows a schematic energy level diagram. The photon intensity I_s of a satellite line, per unit volume is given by

$$I_s = 2.06 \times 10^{-16} \frac{N_{He} N_e}{T_e^{3/2}} \frac{g_s}{g_1} \frac{A_r A_a}{(A_a + \Sigma A_r)} \exp\left(-\frac{E_s}{kT_e}\right), \tag{1}$$

where N_{He} and N_e are the densities of helium-like ions and electrons respectively, E_s is the energy of the satellite level of statistical weight g_s above that of the helium-like ground state of statistical weight g_1. A_a and A_r are the transition probabilities for decay of the state s by autoionization and stabilizing radiation respectively. T_e is the electron temperature in degrees Kelvin.

The resonance line intensity is given by

$$I = N_{He} N_e C, \tag{2}$$

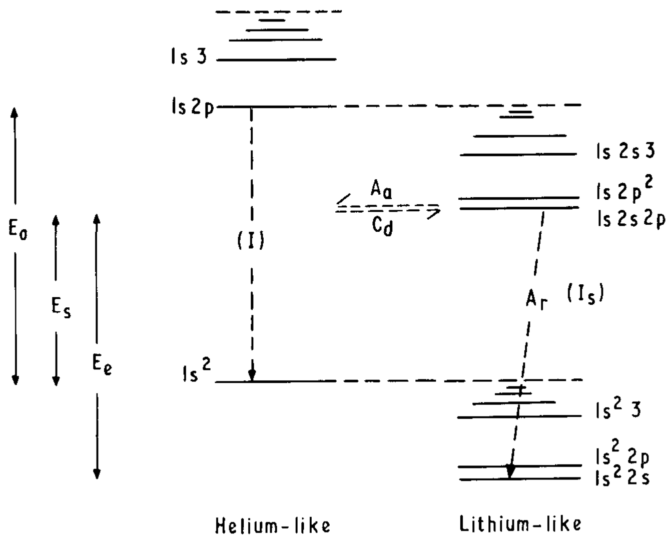

Fig. 2. Energy level diagram, showing the helium-like and satellite transitions.

where C is the collisional excitation rate coefficient. We use the approximate expression due to Van Regemorter (1962) giving

$$C = 1.7 \times 10^{-3} \frac{f}{E_0 T_e^{1/2}} P \exp\left(-\frac{E_0}{kT_e}\right), \tag{3}$$

where E_0 is the excitation energy in eV and P is a slowly varying function of E_0/kT_e. f is the oscillator strength for the transition, but is used here as an adjustable parameter in order to overcome the approximate nature of the expression. We use $f=0.75$ for laboratory plasmas in which both $1s\ 2s\ ^2S$ and $1s\ 2p\ ^1P$ contribute, and 0.55 for astrophysical plasmas, in which $1s\ 2s\ ^1S$ decays by two-photon emission. Combining (1) (2) and (3) gives for the ratio of satellite to resonance line intensities

$$\frac{I_s}{I} = \frac{1.2 \times 10^{-13}}{T_e} \frac{g_s\ E_0}{g_1\ Pf} \frac{A_r A_a}{(A_a + \Sigma A_r)} \exp\left(\frac{E_0 - E_s}{kT_e}\right) \tag{4}$$

Note that the ratio is independent of density but varies inversely with T_e (the exponential is a slow function also of T_e). For low Z ions below say silicon the ratio

$$\frac{A_a}{(A_a + \Sigma A_r)} \approx 1, \tag{5}$$

and can be neglected. Then A_a need not be known. If we look at the Z dependence of Equation (4) we must assume some sensible Z dependence for T_e. If E_0/T_e is taken as independent of Z, then the ratio varies as Z^4 through the term A_r. Then we expect satellites of the order of 1% of the resonance line in oxygen, increasing to ~100% by iron, as is in fact observed.

For production of the satellite lines by inner-shell excitation, one obtains

$$I_s' = N_{Li} N_e C' \frac{A_r}{(A_a + \Sigma A_r)}, \tag{6}$$

where N_{Li} is the population density of lithium-like ions and C' is the collisional excitation rate coefficient for inner-shell excitation. Note that this mechanism favours lines with low A_a, ie non-autoionizing lines. Relative to the resonance line, the inner-shell excited satellite line intensity is given by

$$\frac{I_s'}{I} = \frac{N_{Li}}{N_{He}} \frac{C'}{C} \frac{A_r}{(A_a + \Sigma A_r)}. \tag{7}$$

The temperature dependence is contained entirely in the term N_{Li}/N_{He}, which depends also on departures from steady state ionization, ie whether the plasma is ionizing or recombining.

Both Equations (4) and (7) must also be corrected for the contribution to the resonance line intensity due to dielectronic recombination involving higher principal quantum numbers. For this correction, which does not exceed 10%, it is adequate to use Burgess's (1965) approximate expression, after subtracting that part of the dielectric recombination rate which results in resolved satellite lines.

5. Laboratory Experiments

Experiments by Gabriel and Paget (1972) using a theta-pinch plasma have been designed to compare the intensity ratios of these satellites with the values predicted from Equations (4) and (7) above. The device produced a transient ionizing homogeneous plasma with electron temperatures of 2 or 3×10^6 K and densities of 1 or 8×10^{16} cm^{-3}. Measurements were made using oxygen and nitrogen lines, on the two stronger satellites, designated (a) and (f) in Table I. Measurements made at the time of peak emission of the resonance line showed agreement with the calculated result from Equation (4), to within the experimental errors of $\pm 25\%$. Equation (7) predicts a zero contribution from inner-shell excitation at these conditions. Figure 3 shows a comparison of these data with the calculated curves as a function of T_e.

A study of the full time-histories of the emitted intensities showed that early in the discharge pulse, when the emitted intensity in both resonance and satellite lines was small, a period exists when the dominant mechanism of production is by inner-shell excitation. At this earlier time, the electron temperature T_e is an order of magnitude larger than that required to give the prevaling value of N_{Li}/N_{He} in a steady state. The condition is thus one of extreme transient ionization, and this appears to be a necessary requirement for inner-shell ionization to become dominant in elements around oxygen. Here also the experiment showed good agreement with the predictions from Equation (7).

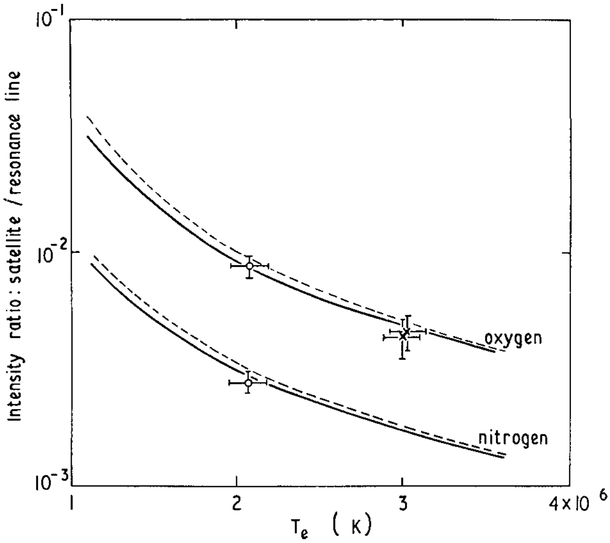

Fig. 3. A comparison between the computed satellite to resonance line ratios (full lines) and experimental observations (data points). The dashed curves are before applying the correction for the dielectronic recombination contribution to the resonance line (Gabriel and Paget, 1972).

6. Calculations for Higher Z Ions

There are two problems in carrying the above theory to more highly ionized ions. First, the LS coupling approximation becomes inadequate above say silicon. The other problem concerns calculations of intensities above say neon, at which point the relationship in Equation (5) is no longer valid. It then becomes necessary to know the autoionizing rates A_a.

Gabriel (1972) has carried out computations both for wavelengths and intensities from carbon up as far as copper, a limit chosen since some laboratory experiments are known to be in progress using copper. The method used for computing wavelengths follows that used earlier for lower ions (Gabriel and Jordan, 1969a) but with in this case the transformation to intermediate coupling. By using the energy difference between the helium-like transition and the satellite energies, many of the relativistic corrections cancel. The remaining errors are of low order, ie linear in Z, and have been corrected for by using reliable experimental observations for low Z, in particular for carbon oxygen and magnesium.

To compute the predicted intensities it was necessary also to know values for A_r and A_a. A_r was obtained directly from the Hartree-Fock wave-functions. Values of A_a were obtained from the $Z=\infty$, LS coupling calculations of Propin (1961). Both A_r and A_a were then transformed to intermediate coupling, using the eigenvectors derived from the energy calculations. Both the dielectronic recombination and the inner-shell excitation contributions were calculated. Since only some satellites are effected by inner-shell excitation, ie at low densities only those from the $1s\ 2p\ 2s$

configuration, it becomes possible in principle to use the measured relative intensities to determine both the temperature and the transient state of the ionization.

The region covered by these satellites also includes the intercombination and forbidden $1s^2\ {}^1S$–$1s\ 2s\ {}^3S$ line of the helium-like ion. Since these can confuse the interpretation, their positions and intensities must also be known. The intercombination line has therefore been included in the above calculation. For the forbidden line, since it is not due to a $1s$–$2p$ transition, the cancellation of higher order relativistic terms is incomplete, and for this the calculated wavelength by Vainstein and Safronova (1971a) was used. The intensities of the helium-like lines were obtained from the theory of Gabriel and Jordan (1969b) as revised by Freeman *et al.* (1971). For the higher Z ions, the parameters F and G in this theory must be further adjusted in order to fit with the observations.

An alternative approach to the calculation of the satellite wavelengths and intensities has been made by Vainstein and Safronova (1971b). They used a Z-expansion method for the wavelengths, and computed also values of A_r and A_a. Although the wavelength agreement is good, their values for A_a and A_r differ appreciably from those used by Gabriel (1972). There are reasons for believing that important errors exist in their values for these parameters as given in the preliminary preprint received.

Some satellite lines in high ions have been identified as inner-shell $1s$–$2p$ transitions in ions with 4 or more electrons. It is difficult to calculate the intensities of such features, which can often be produced by a number of different recombination and excitation processes. All of these processes require a combination of high electron energies with low stages of ionization, ie a transient ionizing plasma. Such conditions are more likely to be found in laboratory sources than in astrophysical plasmas.

7. Observations in High Z Ions

Since the satellite intensities increase with Z, the observation of satellites in low Z ions from the Sun is not easy. At the time of writing there have been no such lines reported below magnesium, although it is understood that recent unpublished data includes solar satellite lines in oxygen and neon. However, studies of solar active regions and flares have given data on such satellites from aluminium, silicon, sulphur, calcium and iron. Many of these observations are reviewed in the papers by Doschek (1972) and Walker (1972) at this conference. The wavelength resolution of these solar observations is often insufficient to separate all the lines and carry out a detailed interpretation. However, a recent spectrum recorded from the satellite Intercosmos 4 (Grineva *et al.*, 1971) has recorded an excellent iron spectrum with a resolution of 4×10^{-4} Å. This is shown in Figure 4, together with a computed spectrum by Gabriel (1972). In order to obtain the best intensity fit the electron temperature used in the computations was 26×10^6 K. with an Fe XXIV/Fe XXV population ratio equivalent to 50×10^6 K. These conditions would imply a recombining plasma. Grineva *et al.* also included preliminary classifications of the features in their spectrum, which are in good agreement

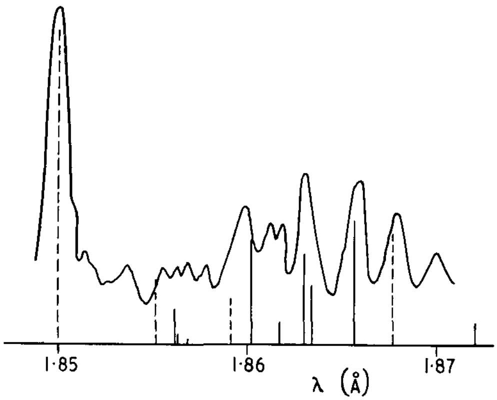

Fig. 4. The solar flare spectrum near 1.8 Å obtained from the Intercosmos-4 satellite (Grineva *et al.*, 1971). The vertical lines represent the spectrum computed by Gabriel (1972). Full lines are for lithium-like ions, dashed lines for helium-like ions.

with those implied by the comparison shown in Figure 4. The feature at 1.870 has been attributed by Grineva *et al.* to an inner-shell transition in Fe XXIII.

Spectra from helium-like ions up to iron have also been obtained using laboratory sources such as the plasma-focus or low-inductance sparks. These show characteristically a set of satellite lines which can be clearly attributed to inner-shell transitions in 3, 4, 5, 6 etc. electron ions, often extending as far as the Kα X-ray line of the neutral atom. Such spectra are shown by Elton and Lie (1972) and Schwob and Fraenkel (1972) in papers at this meeting. The spectral resolution in these experiments has not so far been sufficient to resolve the 3-electron ion satellites in the same manner as in Figure 4, and thus to determine the transient state. However it appears probable that these plasmas are always in a transient ionizing state and thus give spectra very different from those obtained from the solar flare plasma.

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DISCUSSION

G. Tondello: Have you been able to observe a difference in the width of these satellite lines with respect to the 'normal' lines?

A. H. Gabriel: No. This would be very valuable, but the autoinizing widths are very small.

G. Tondello: Have you been able to measure the intensities of the satellite and normal lines in the case of CV?

A. H. Gabriel: No. This is due to technical difficulties in the experiment. There is a coincidence between their wavelength and that of some impurity lines.

A. B. C. Walker: We have observed satellites to the hydrogen-like lines which are in the helium-like system. Have you done any calculations on these lines, there is more theoretical data available for their parent states.

A. H. Gabriel: No. This would be easier theoretically, but the measurements are more difficult since the lines are weaker.

A. B. C. Walker: Are the hydrogen-like line satellites weaker only because of temperatures effects.

A. H. Gabriel: I think this may be due to the nature of the relative changes in ionization potential along an ionization sequence.

G. A. Doschek: Do you have any explanation for why the intercombination line is so weak in the iron spectrum obtained by Mandelshtam and his colleagues at the Lebedev Institute?

A. H. Gabriel: I do not think that the intercombination line is unexpectedly weak, when compared with the forbidden line.