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# Atomic Physics Calculations Relevant to Solar Flare Spectra

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# Atomic physics calculations relevant to solar flare spectra

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Solar flare spectra in the ultraviolet and X-ray wavelength regions are rich in emission lines from highly ionized ions, formed at temperatures around $10^7$ K. These lines can be used as valuable diagnostics for probing the physical conditions in solar flares. Such analyses require accurate atomic data for excitation, ionization and recombination processes. In this paper, we present a review of work which has already been carried out, in particular for the *Solar Maximum Mission* observations, and we look to future requirements for *Solar-A*.

## 1. Introduction

The study of solar flares has generated a great deal of activity in the field of atomic physics. Conversely, the calculation of atomic data and the development of spectroscopic diagnostics has contributed significantly to our knowledge of solar flares. It is difficult to know where to begin in the review of this subject. A good starting point is perhaps the summer of 1977, before the launch of the *Solar Maximum Mission* (*SMM*), when a workshop was held at the Culham Laboratory on 'Atomic data needs for *SMM*'. This was the first of many such meetings and workshops on this subject, held in the U.K. but with international participation. The chairman of the organizing committee for that meeting and a key organizer for many subsequent gatherings was Peter McWhirter. He coordinated the U.K. group of workers in this field, commonly known as the QUACS consortium. This involved groups at Queen's University of Belfast (QUB), University College London (UCL), Astrophysics Research Division, Cambridge University and Strathclyde University and subsequently other participants. Between us, we produced a manual of 'Atomic data for *SMM*' covering the ultraviolet (UV) and the X-ray wavelength regions and a regular newsletter '*SMM* – Solar and Atomic Physics' which had a worldwide distribution. We also, of course, produced many individual publications on analyses of *SMM* spectra and related atomic calculations. The aim of this paper is to review what has been achieved over the past decade by the QUACS consortium and other atomic physics groups in Europe (particularly in France), in the U.S.A. and Japan. Useful reviews have been published earlier by Gabriel & Mason (1982) and Doschek (1985). This paper will focus on *SMM* but will also refer to other solar flare observations and will look towards future missions such as *Solar-A* with a view to asking what further calculations are required and how can these be obtained?

In §2, electron excitation rates are discussed for different categories of ions: He-like ions; highly ionized ions in the X-ray and XUV wavelength regions; coronal ions in the UV wavelength region; transition region ions. In §3 ionization and

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recombination processes are considered in relation to the formation of satellite lines, inner-shell transitions and ionization balance calculations. The consequences of non-equilibrium processes are considered.

## 2. Electron excitation rates

The users of atomic data are often confronted by a vast number of different calculations each claiming to be the most accurate yet obtained! The proponents are not necessarily unbiased in their assessment of the work from other groups and are sometimes over enthusiastic in supporting their own particular methods. On the whole, this healthy competition has resulted in the production of high-accuracy atomic data from different groups and an intercomparison of results which has led to a better understanding of the strengths and limitations of different techniques. Much of the work on electron scattering has been orientated towards analyses of solar spectra. The problem essentially breaks into two parts, the representation used for the target wavefunctions and the technique used to solve the electron scattering problem.

For complex ions, it is essential to obtain a good representation of the target ion before carrying out a calculation of electron collision rates. Configuration interaction between different configurations must be taken into account. For example, the ground configuration of $\mathrm{Ca}^{\mathrm{XV}}$, $2\mathrm{s}^2 2\mathrm{p}^2$, interacts very strongly with the excited configuration $2\mathrm{p}^4$. Any accurate electron scattering calculation would need to include both these configurations. For systems more than a few times ionized, the configurations in the same complex interact most strongly, that is configurations which have the same principal quantum number and the same parity (even or odd). Calculations for ions in the $n = 2$ complex are reasonably straightforward, since the number of configurations required is quite small. However, for ions in the $n = 3$ complex (e.g. $\mathrm{Fe}^{\mathrm{XIII}}$, $3\mathrm{s}^2 3\mathrm{p}^2$) the problem is much greater and many configurations need to be included in the calculation. The calculation of electron excitation rates for transitions between configurations with different principal quantum numbers (e.g. $\mathrm{Fe}^{\mathrm{XIX}}$, $2\mathrm{s}^2 2\mathrm{p}^4$–$2\mathrm{s}^2 2\mathrm{p}^3 3\mathrm{d}$) also requires a large number of configurations to obtain results of acceptable accuracy. Even when many configurations are included, the target is sometimes still not good enough and other techniques are used to improve it, such as including ‘pseudo orbitals’ or ‘non-spectroscopic’ orbitals, which are used solely to simulate neglected configurations. Another technique is to use semi-empirical fitting to observed energy levels. It is very important for coronal and flare ions to take account of spin–orbit and other relativistic interactions in the target. The electron scattering calculation is usually carried out in LS coupling and the target is then transformed into intermediate coupling to produce the collision strengths. Some programs have recently been developed to solve the electron collision problem relativistically. Such methods become important for elements heavier than iron, such as those found in tokamaks. In any assessment of electron scattering calculations, it is necessary first to examine carefully the target.

Several different methods are commonly used to carry out electron scattering calculations. Close coupling calculations (CC) solve a set of integro-differential equations, the channels (target state + scattering electron) being coupled together. In the U.K., two sets of CC programs have been extensively used, RMATRX (Berrington *et al.* 1978) and IMPACT (Crees *et al.* 1978) developed at QUB and UCL. The CC approximation is the most accurate method of solving the electron scattering problem, but it is also the most expensive in terms of computer resources. As a consequence, it is often necessary to truncate the size of the target, that is the number of configurations included. Many high accuracy CC calculations have been carried out for ions between configurations with $n = 1$ or $n = 2$ principal quantum numbers, but fewer exist for more complex ions with $n = 3$ or $n = 4$ configurations. In the distorted wave approximation (DW), the channels are not coupled, the scattering electron sees a central potential. The DW approximation is usually very good for systems more than a few times ionized. Because it is a relatively straightforward approximation, it is possible to use very sophisticated targets with a large number of configurations. The DW program developed at UCL (DSTWAV) (Eissner 1972; Eissner & Seaton 1972) has been extensively used for ions of solar interest. Direct comparisons between DSTWAV, RMATRX and IMPACT for optically allowed transitions of coronal ions give agreement within a few percent (Burgess *et al.* 1989, 1991). In the Coulomb–Bethe approximation (CB), Coulomb waves are used and it is assumed that the scattering electron does not penetrate the target. This is quite a crude approximation, but is used to complement other calculations for high partial wave values of the incoming electron. The resonance contribution to the collision strength is often very important for forbidden and intersystem transitions, particularly for the lower ion stages present in the transition region. Badnell *et al.* (1991) showed how resonance structures could be accounted for with the DW approximation and made detailed comparisons with RMATRX calculations.

Several compilations of theoretical electron excitation rates are now available for specific iso-electronic sequences, He-like (Kato & Nakazaki 1988), Li-like (Cochrane & McWhirter 1983), Be-like ions (Safronova *et al.* 1990) and more generally (Itikawa 1984; Gallagher & Pradhan 1985). Several workshops have also been held in the U.K. to assess atomic data (Eissner 1985; Eissner & Kingston 1988). Besides the work with the UCL and QUB programs, electron excitation and ionization calculations for ions of solar interest have been carried out by several other groups; for example, Sampson and colleagues at the Pennsylvania State University have carried out a vast number of calculations. Laboratory measurements of collisional electron–ion rate coefficients for ionization, dielectronic recombination and excitation are now becoming available for many ions. A good review of quantitative spectroscopy of plasmas containing multiply ionized atoms is given by Griem (1988). Much of this work has been carried out by the atomic physics group at Maryland University. Recent breakthroughs in laboratory techniques, such as the merged beam electron-energy loss technique, are now enabling the measurement of absolute electron-impact cross-sections of multiply charged ions. One of the first such measurements is reported by Wohlin *et al.* (1991) for $\mathrm{Si}^{3+}$. Excellent agreement is found with the calculations of Badnell *et al.* (1991).

### (*a*) *Helium-like and hydrogen-like ions*

Spectral lines from the helium-like ions are particularly important in the study of solar flares. Consequently, a lot of effort has gone into the calculation of accurate atomic data for these lines. The He-like ions $\mathrm{Ca}^{\mathrm{XIX}}$ and $\mathrm{Fe}^{\mathrm{XXV}}$ were extensively observed with the X-ray polychromator's bent crystal spectrometer (XRP-BCS) on *SMM*. These and other He-like ions have been observed with numerous instruments, including the XRP flat crystal spectrometer (FCS), the SOLFLEX and SOLEX instruments on *P78-1* and the *Hinotori* instruments. The $\mathrm{O}^{\mathrm{VII}}$ (McKenzie *et al.* 1980*a*; Keenan *et al.* 1984*a*), $\mathrm{Ne}^{\mathrm{IX}}$ and $\mathrm{Mg}^{\mathrm{XI}}$ (Wolfson *et al.* 1983; Keenan *et al.* 1984*b*; Doyle &

Keenan 1986; Keenan *et al.* 1986; Linford *et al.* 1988) line intensity ratios have been used to determine electron density values for solar flares. Other He-like ions, which have been observed in solar flares, have also been studied: Si$^{\text{XIII}}$ (Keenan *et al.* 1990) and S$^{\text{XV}}$ (McCann & Keenan 1988). A great effort has been put into calculations for the satellite lines $1s^2nl$–$1s2pnl$ ($n \geqslant 3$) which blend with the resonance lines $1s^2$–$1s2p$ (Bely-Dubau *et al.* 1979*a*, *b*). A complete analysis of all the atomic processes which contribute to the observed emission spectra for the He-like ions was carried out by Bely-Dubau *et al.* (1982*a*, *b*). The theoretical and observed solar spectra agree well, except for the intercombination line $y$ ($1s^2\ {}^1S_0$–$1s2p\ {}^3P_1$). Dubau *et al.* (1991) suggest that non-equilibrium conditions, such as suprathermal electrons or huge electric fields could be responsible for this unexplained discrepancy.

The spectra from the H-like ions and their satellite lines are discussed by Dubau *et al.* (1981, 1991). The Fe$^{\text{XXVI}}$ lines were recorded by *SMM* during the early phase of operations and were observed extensively by *Hinotori*. The theoretical intensity ratio of the two L$\alpha$ lines should be around 0.5, however, the observed ratio is not consistent with the theoretical value. Dubau *et al.* (1991) suggest different processes which may cause this anomalous ratio, including suprathermal electrons or huge electric fields. McWhirter & MacNeice (1987) studied *SMM* solar flare spectra of the Mg$^{\text{XII}}$ doublet. They found that the observed intensity ratio was inconsistent with the theoretical value (Ljepojevic *et al.* 1984) and suggest non-negligible opacity as an explanation.

### (*b*) *Highly ionized iron and calcium ions*

The solar flare spectrum in the XUV and X-ray wavelength regions is characterized by lines from highly ionized iron ions. The wavelength region 1–25 Å† has been extensively covered by different instruments, such as SOLEX on *P78-1* and the XRP-FCS on *SMM*. Identifications for lines in the 6–23 Å wavelength region are given by McKenzie *et al.* (1980*b*) and Phillips *et al.* (1982). Many $n = 2$ to $n = 3$, $n = 4$, $n = 5$ transitions are recorded for the highly ionized iron ions (Fe$^{\text{XIX}}$–Fe$^{\text{XXIV}}$) (Fawcett *et al.* 1987). Electron scattering calculations for these transitions are quite complex. It is necessary to include a large number of configurations for a good target representation. For example, recent DSTWAV calculations for Fe$^{\text{XIX}}$ have been published by Bhatia *et al.* (1989). They found it necessary to include seven configurations in the electron scattering calculations and even then, perfect agreement was not obtained with the observed wavelengths or spectral line intensities from *SMM*. Calculations for Fe$^{\text{XX}}$ (Mason & Bhatia 1983), Fe$^{\text{XXI}}$ (Mason *et al.* 1979), Fe$^{\text{XXII}}$ (Mason & Storey 1980) and Ca$^{\text{XV}}$ (Bhatia & Mason 1986*b*) were somewhat simpler since the target had fewer electrons. Fe$^{\text{XXIII}}$ is an interesting case. Calculations for this ion were carried out by Bhatia & Mason (1981, 1986*a*) and it was found that the electron collision strengths between $2s^2$ and $2s3s$, $2s3d$ are stronger than those between $2s^2$ and $2s3p$. This seems very surprising, since the latter is an electric dipole transition. This unusual phenomena is known to also occur in other ion sequences. From their calculations, Bhatia & Mason were able to make a detailed comparison with SOLEX observations. A similar work was carried out for the iso-electronic Ca$^{\text{XVII}}$ ion (Bhatia & Mason 1983), which emits strong lines at around 20 Å. New calculations have just been completed by Loulergue, Cornille and Dubau for Fe$^{\text{XVII}}$ and Fe$^{\text{XVIII}}$. These authors have used a modified form of DSTWAV to calculate electron excitation rates for the mass of spectral lines around 13 and 16 Å,

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† $1\ \text{Å} = 10^{-10}\ \text{m} = 10^{-1}\ \text{nm}$.

including $Fe^{XVI}$ satellite lines. They have made detailed comparisons with *SMM* observations.

The $n = 2$ to $n = 2$ transitions of $Fe^{XVIII}$–$Fe^{XXIV}$ fall in the wavelength region 90–200 Å. Only one set of solar flare data exists for this important wavelength region. That was obtained with the Goddard Space Flight Center's grating spectrometer on the *OSO-5* satellite. A comprehensive review of the solar observations and the atomic calculations is given in Mason *et al.* (1984). References to work by Mason and collaborators are for $Fe^{XIX}$ (Loulergue *et al.* 1985), $Fe^{XX}$ (Bhatia & Mason 1980), $Fe^{XXI}$ (Mason *et al.* 1979), $Fe^{XXII}$ (Mason & Storey 1980), $Fe^{XXIII}$ (Bhatia & Mason 1981). The electron scattering calculations for these types of transitions are reasonably straightforward and more recent work does not differ significantly from these early calculations.

The wavelength region 10–95 Å also contains spectral lines of diagnostic interest. A solar flare spectrum in this wavelength region was obtained by Acton *et al.* (1985) with a grazing incidence X-ray spectrograph (XSST) aboard a rocket. The electron density diagnostic potential for wavelength region was extensively explored by Brown *et al.* (1986). Several lines from He-like ions were observed together with $n = 2$ to $n = 3$ and $n = 3$ to $n = 4$ transitions from other ions. Accurate atomic data for these transitions is sparse and sometimes non-existent. Simulated spectra in this wavelength region have been produced by several authors (see, for example, Mewe & Gronenschild 1981; Landini & Monsignori-Fossi 1989), but the approximations used to estimate some of the line intensities are questionable. In particular, there are a number of very strong $Fe^{XVI}$ lines. New calculations have recently been carried out for the $Fe^{XVI}$ $n = 3$ to $n = 4$, $n = 5$ transitions by Cornille, Dubau, Loulergue and Mason. These agree with independent results by Sampson *et al.* (1990). It is found that the strongest collision strengths are associated with the $3s^2$ to 3s4d transitions, not the dipole transitions $3s^2$ to 3s4p as might be expected. This has significant consequences for the production of simulated spectra, which are used not only for solar analyses, but also for astrophysical observations. A similar phenomena in $Fe^{XV}$, gives rise to unexpectedly strong spectral lines which are recorded in the XSST spectra. New calculations for $Fe^{XV}$ have just been completed by Bhatia & Mason.

### (*c*) *Coronal ions*

The UV observations made by the NRL-A instrument (171–630 Å) on the *Skylab* Appollo Telescope mount (ATM) have provided a wealth of spectra on many different solar phenomena and in particular on solar flares. A review of all the papers covering this topic is beyond the scope of this paper. Much of the early work is covered in the *Skylab* Workshop series books on solar active regions (Dere & Mason 1981) and solar flares (Moore *et al.* 1980). A detailed study of electron density diagnostics and the corresponding atomic data is given in Dere *et al.* (1979) and Mason (1991). Here we make a few comments with regard to atomic calculations for particular ions. Spectral lines from the ion $Ca^{XV}$ are very useful as electron density diagnostics for solar flares. Electron collision data for this ion was given in Mason (1975) and extended in Dere *et al.* (1979). The DSTWAV code was used. A subsequent analysis of NRL-A data (Keenan *et al.* 1988) used atomic data obtained with the QUB RMATRX codes. The atomic data and electron densities derived are in very good agreement with the earlier work. The transitions are all $n = 2$ configurations and therefore relatively straightforward to treat.

The iron ions ($Fe^{IX}$–$Fe^{XV}$) pose a much greater problem since they arise from $n = 3$

configurations. Feldman *et al.* (1978) suggested using Fe$^{\text{IX}}$ line ratios to determine electron densities in solar flares. Their intensity ratios were based on DSTWAV calculations by Flower (1977*b*). It has subsequently been discovered that the indexing in Flower's collision strengths was muddled up, which particularly effected the transitions between the metastable levels in the excited configuration. Papers based on his calculations need to be re-assessed. New calculations have recently been published for Fe$^{\text{XIII}}$ (Fawcett & Mason 1989*a*) and Fe$^{\text{IX}}$ (Fawcett & Mason 1991) using DSTWAV and a new technique for improving the target. All the important configurations were included and then some optimization of the wave functions was carried out to fit the observed and theoretical wavelengths (Fawcett & Mason 1989*b*). A lot of work has also recently been done on Fe$^{\text{XII}}$ (Tayal *et al.* 1989) and Fe$^{\text{XV}}$ (Dufton *et al.* 1990) using the QUB RMATRX codes. The new calculations for Fe$^{\text{XII}}$ differ by about 20% from earlier DISTWAV results (Flower 1977*a*) and electron densities derived for flares and active regions are consistent with those from Fe$^{\text{XIII}}$ and Fe$^{\text{XIV}}$ lines. In contrast, the Fe$^{\text{XV}}$ line ratios are inconsistent with the observations and continue to cause problems even with the new high-accuracy calculations! A substantial amount of work is still required to refine the calculations for these iron ions. A very comprehensive analysis of the UV spectrum of a particular flare has recently been published (Doyle & Widing 1990; Widing & Doyle 1990).

### (*d*) *Transition region ions*

Spectral lines from transition region ions fall predominantly at longer wavelengths (600–2000 Å). Many solar spectra have been obtained in this wavelength region by instruments such as those on *Skylab*'s ATM (S0555, S082B), the high resolution spectrometer and telescope (HRTS) and *SMM*s UV spectrometer and polarimeter (UVSP). It has been suggested that the heating of the solar corona is produced by 'nano-flares' (Parker 1988) which exhibit themselves in the UV as dynamic phenomena. Recent reviews of UV spectral diagnostics are given by Mason (1988, 1990). A tremendous amount of work has been carried out for transition region ions by members of the QUACS consortium. For these ions it is usually very important to determine the resonance contribution to the electron collision cross section. Particular mention must be made of the work at QUB with the RMATRX codes, which has provided high accuracy electron excitation rates for many transition region ions. For example, the Be-like (C$^{\text{III}}$, O$^{\text{V}}$, Ca$^{\text{XVII}}$, Fe$^{\text{XXIII}}$), C-like (O$^{\text{III}}$, Ne$^{\text{V}}$, Mg$^{\text{VII}}$, Si$^{\text{IX}}$, Ca$^{\text{XV}}$), Na-like (Al$^{\text{III}}$, Si$^{\text{IV}}$), Mg-like (Al$^{\text{II}}$, Si$^{\text{III}}$, S$^{\text{V}}$) and Al-like (S$^{\text{IV}}$) ions have been exhaustively studied. It is impossible to refer here to all the papers on transition region and coronal ions published by the QUB group. A compilation of references of work with the RMATRX codes is available on request from QUB.

Another transition region ion which has received a lot of attention is O$^{\text{IV}}$. The ratio of line intensities within this ion or relative to Si$^{\text{IV}}$ have been used to determine electron density. High time resolution observations of these lines with *SMM* UVSP indicated electron density enhancements of more than an order of magnitude, which were correlated with hard X-ray bursts during solar flares (Cheng *et al.* 1981; Cheng & Tandberg-Hanssen 1986). In fact, the transition region emission implies the existence of continual small scale activity. Hayes & Shine (1987) studied the characteristics of these bursts and explored the potential of the O$^{\text{IV}}$ diagnostic.

The radiative properties of the solar plasma is dependent on atomic processes, excitation rates and ionization balance. Bruner & McWhirter (1988) looked in detail at the radiative power loss function for transition region and coronal ions.

In recent years, an international collaboration called the Opacity project has been working to calculate photoionization data for astrophysics. This major project, which has produced a tremendous amount of atomic data, is now completed and results are being published. This was coordinated by Professor M. J. Seaton at UCL, in collaboration with QUB and atomic physics groups in the U.S.A., Europe and South America. An extension of this work is planned, called the Iron project, which will obtain electron excitation rates for many ions. This will be of particular relevance to future work on solar spectra.

### (*e*) *Assessment and storage of atomic data*

Many large atomic databanks now exist. Several of these are associated with fusion research projects (in the U.K. at JET; Summers & Wood 1988). A major U.K. atomic databank is at QUB. Several different groups have also developed computer packages for plotting and assessing electron excitation data. One such package has been developed by Burgess & Tully (1991). The aim of this interactive graphics package is to provide a simple method of presenting results from electron scattering calculations for use in astrophysical analysis programs (Burgess *et al.* 1988, 1989; Lang *et al.* 1990). Reduced collision strengths are plotted on a reduced energy scale which runs from 0 (threshold) to 1 (infinite energy). The high-energy limit is obtained from the oscillator strength for optically allowed transitions. These data are fitted automatically or interactively by a spline curve. The thermally averaged collision strength can be obtained and plotted on a reduced temperature scale in a similar manner. This method of analysing electron excitation results is very efficient at exposing any deficiencies in the atomic data. It also provides a very compact way of storing data for solar analyses. The package can run on various microcomputers and is available, by arrangement with Dr Burgess.

## 3. Ionization and recombination processes

### (*a*) *Dielectronic satellite line-spectra and inner-shell transitions*

The satellite line spectra in the X-ray wavelength region has perhaps attracted the most attention over the past decade. Excellent solar flare observations have been obtained with different instruments, including *SMM* XRP-BCS, SOLFLEX and *Hinotori*. In particular, the satellite lines from calcium and iron ions have been thoroughly analysed and their diagnostic potential has been fully explored (Bely-Dubau *et al.* 1982*a*, *b*). Several good reviews have been written on this subject, notably Dubau & Volonte (1980) and Doschek (1985). The French groups at Meudon and Nice Observatories developed a computer code to analyse observed spectra by adjustment to a synthetic spectra which gave both the electron temperature and ionization ratios. This interactive package has been used widely to analyse solar flare spectra, in particular from *SMM* XRP-BCS. A more sophisticated version was developed to deal with more complicated features, such as line shifts and broadening seen during the impulsive phase of flares.

The inner shell transitions in Ca and Fe ions have been observed in solar flare spectra from SOLFLEX (Doschek *et al.* 1981; Seely & Doschek 1989), *SMM* (Phillips *et al.* 1983; Lemen *et al.* 1984) and *Hinotori* (Tanaka *et al.* 1982). Accurate wavelengths have been calculated for these lines using different atomic structure techniques, including the multi-configuration Dirac–Fock program by Grant and his colleagues at Oxford University, methods developed by Safronova and Vainstein and other Russian colleagues, the Hartree–Fock code developed by Cowan at Los Alamos and the UCL SUPERSTRUCTURE code. The spectral lines are formed by both dielectronic recombination and collisional inner-shell excitation.

### (b) *Ionization equilibrium calculations*

A very good recent review of ionization and recombination processes in hot astrophysical plasmas is given by Mewe (1990). This updates the earlier work by Arnaud & Rothenflug (1985).

The general formula by Burgess (1965) is often used to calculate dielectronic recombination rates. This formula has withstood the onslaughts of time remarkably well. For example, a recent RMATRX calculation by Terao & Burke (1990) for Li-like aluminium presented results which were a factor 2 to 3 times different from those obtained with the general formula. However, Terao & Burke's results have been shown to be incomplete by Badnell (1990). He has developed the UCL SUPERSTRUCTURE program (Eissner *et al.* 1974), to calculate autoionization rates (AUTOSTRUCTURE; Badnell 1985). Using this program and extending Terao & Burke's results, he obtains agreement with Burgess's general formula to within 30%. He has used this AUTOSTRUCTURE package extensively to calculate dielectronic recombination rates for ions of astrophysical interest and for comparison with laboratory work. In particular, he has published results for the solar flare ions, $Fe^{+21}$, $Fe^{+22}$, $Fe^{+24}$ (Badnell 1986*a*, *b*, 1987). His results are in good agreement with Burgess's general formula.

External electric fields can have an important effect on dielectronic recombination (DR) rates. Field ionization effects lead to a decrease in DR rate coefficient, while field mixing effects lead to an increase in the DR rate coefficient. This is investigated by Krylstedt *et al.* (1990) for oxygen ions. They find that overall, strong fields produce a significant decrease in the DR rate coefficient at peak temperatures. They find good agreement with the Burgess general formula II which includes both field mixing and ionization effects. If electric fields are strong in solar flares, it is essential to pursue this problem vigorously.

A simple general formula for the total ionization cross-section, which allows for inner-shell excitation and autoionization, was proposed by Burgess & Chidichimo (1983). This was an extension of an earlier work by Burgess *et al.* (1977). Burgess & Chidichimo found that the general formula agreed with all available experimental data to within 23%. Much effort has recently gone into the calculation and experimental measurement of electron impact ionization cross-sections. These studies have revealed that indirect processes can make a greater contribution to the ionization cross-section than direct processes. For example, the work by Chen *et al.* (1990) discusses the contribution of resonant excitation double autoionization to the electron impact of $Fe^{+15}$. Direct ionization and excitation–autoionization cross-sections are being computed with relativistic DW methods by Moores at UCL.

Most of the time during flares, the *SMM* spectra indicate that the plasma is in ionization equilibrium. It has therefore been possible to derive the ionization equilibrium ratios for $Fe^{XXIV}/Fe^{XXV}$ and $Fe^{XXIII}/Fe^{XXV}$ (Antonucci *et al.* 1987) and for $Ca^{XVIII}/Ca^{XIX}$ (Antonucci *et al.* 1984) from *SMM* and *Hinotori* spectra. There is a significant discrepancy between the observed and theoretical values, even with recent calculations (Arnaud & Rothenflug 1985).

Non-equilibrium ionization processes could occur in the solar atmosphere. The effect of diffusion in the solar chromosphere–corona transition region on the local ionization equilibrium was discussed many years ago by Tworkowski (1975). Interest in non-equilibrium ionization has recently focused on mass flows in coronal loops (Noci *et al.* 1989; Spadaro 1991). Such non-equilibrium ionization conditions would also effect the radiative loss function (Spadaro *et al.* 1990). The time-dependent equations of ionization and recombination were solved for a numerical model of a solar flare based on electron beam heating of the chromosphere by MacNeice *et al.* (1984). For the particular model chosen, departures from steady state ionization balance results were not very large. Mewe *et al.* (1985) solved the hydrodynamic equation for a flaring plasma confined in a one-dimensional magnetic loop structure. They studied deviations from ionization equilibrium and Doppler shifts and simulated Ca and Fe spectra. Raymond (1990) has looked at the interesting case of time dependent ionization of a microflare heated corona and compared his predictions to the average quiet Sun spectrum.

Another non-equilibrium condition which may be important in the transition region and corona is the possible existence on non-maxwellian velocity distributions. These can effect the spectral line intensity ratios, as demonstrated by Keenan *et al.* (1989) for $\mathrm{Si}^{\mathrm{III}}$. Theoretical calculations have recently been carried out of non-maxwellian velocity distributions in the transition region (Ljepojevic & Burgess 1990) and solar flares (Ljepojevic & MacNeice 1988) and their effect on heat conduction in the solar atmosphere (Ljepojevic & MacNeice 1989). It seems likely that non-maxwellian velocity distributions could be prevalent during the initial stages of solar flares. Dubau *et al.* (1991) suggest that this could help to explain the anomalous ionization ratios which have been observed. Inal & Dubau (1987, 1989) studied the excitation of atomic sublevels by directive electrons and the resultant polarization of some of the soft X-ray lines from solar flares.

## 4. Direction of future atomic physics work

The accuracy of atomic physics calculations has improved dramatically over the past decade. Electron scattering calculations by groups using completely different techniques are now converging! Experimental results are becoming available and more reliable for many ions. Substantial work is still required on complex ions, such as iron ions with $n = 3$ configurations. It is still necessary to continue to improve the target wavefunctions. A Briet–Pauli RMATRX package is being developed at QUB which should be particularly useful for heavy ions. Further work is required on direct ionization and excitation–autoionization cross-sections, both theoretical and laboratory measurements. Assessment of electron excitation rates is being carried out in several atomic physics groups. This is time consuming but valuable and should be extended to cover ionization processes as well. Interface programs to use this assessed data for the analysis of solar spectra need to be developed further.

Attention will probably need to focus more on non-equilibrium effects, such as strong electric fields, time dependent ionization and recombination calculations and non-maxwellian velocity distributions. Some progress has already been made in these fields but a lot more work is required.

This paper has concentrated on the progress made over the past decade in atomic physics relevant to solar flares. An immense amount has been achieved since that workshop meeting in 1977. Much of the work which has been described arose as a direct result of participation by various groups in the *SMM* project. We are all now a little older, a little greyer but a lot wiser! It is hoped that future projects such as *Solar-A* will provide a stimulus for further fruitful collaboration between the atomic and solar physics communities.

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