Chromospheric and Coronal Spectra

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Abstract. The interpretation of chromospheric and coronal spectra requires a wide range of accurate atomic data, including ionization and recombination rates, collision strengths for ion-electron collisions, and transition probabilities. Recent projects to improve the atomic physics included in calculations of opacities in stellar interiors have resulted in a large body of new atomic data. Here we discuss some current and potential applications of atomic data to chromospheric and coronal spectra.

1. Introduction

The aim of observing emission line spectra of the Sun and late-type stars is to use the observed fluxes and profiles to make models of the structure of the atmosphere above the photosphere. These models can then be used to estimate the heating required, which can be compared with the predictions of particular non-thermal processes. The principles of the methods used for interpreting ultraviolet and X-ray spectra were established in the 1960's, when observations from space began in earnest, although the interpretation of forbidden lines in the solar coronal spectrum has an even longer history.

In chromospheres many of the strong lines are optically thick and the solution of the radiative transfer equation for a particular line also requires atomic data for other species that contribute to the background opacity. The chromospheric spectra of giant stars with hot coronae show systematic differences from those of main-sequence stars, which arise from the lower gravity of the giants. The chromospheric spectra of the cooler giants and supergiants, which do not appear to have hot coronae, or indeed material hotter than about 2 x 10^4 K, become dominated by processes involving high line opacities (see e. g., the review by Jordan 1988a). Thus, in addition to atomic data for collisional processes, a wide range of photoionization rates and oscillator strengths are needed.

In the transition region and corona most lines are optically thin and the problems of interpretation are simpler. The main requirements are for collisional excitation and ionization rates, and the rates of dielectronic and radiative recombination. Transition probabilities are required for density-sensitive spin-forbidden lines and to determine branching ratios.
Although extreme ultraviolet and X-ray line spectra can be observed from the Sun, most X-ray spectra of stars have very low spectral resolution (a few line spectra were obtained with instruments on the Einstein Observatory and EXOSAT). In this case spectral fitting has to be carried out with computer packages containing a very large number of transitions. However, line spectra of cool stars are now being obtained using the Extreme Ultraviolet Explorer (EUVE) and the traditional methods of finding emission measures from individual lines can be applied. (The emission measure is defined here as \( \int N_e N_H \, dr \).) Interesting comparisons can be made between such emission measures and those derived from spectral fits to broad band spectra, e. g. those obtained with the instruments on the ROSAT satellite.

Some examples of chromospheric atoms and ions of interest will be discussed in Section 2. Lines of highly ionized iron dominate coronal spectra, and the relative ion populations will be discussed in Section 3. These lines are also relevant to the spectra that should be obtained from instruments on SOHO, to be launched in 1995. Section 4 makes some comparisons of the contents of currently available power loss codes and the results of their application to stellar X-ray spectra.

2. Chromospheric Spectra

2.1 The Fe II Spectrum

Fe II is one of the most important ions producing emission lines in stellar chromospheres, and in other astrophysical sources such as active galaxies (see reviews in Viotti, Vittone & Friedjung 1988, which also cover laboratory spectra and related theory). Early observations of the solar uv spectrum allowed numerous lines of Fe II to be identified between about 1300 and 2800 Å (Burton, Ridgeley & Wilson 1967; Burton & Ridgeley 1970). More recent lists with more precise wavelengths include those by Doschek, Feldman & Cohen (1987), Cohen, Feldman & Doschek (1978), and Sandlin et al. (1986). Indeed, Fe II is a major contributor to the total energy loss from the solar chromosphere (Anderson & Athay 1989). Observations with the International Ultraviolet Explorer (IUE) soon showed the importance of lines of Fe II in a wide variety of late-type stars (e. g., Brown, Ferraz & Jordan 1984, Carpenter et al. 1988, Judge & Jordan 1991).

The contribution of Fe II lines in the wavelength range from 2200 to 3100 Å is illustrated in Figure 1 which shows the spectrum of the pre-main-sequence star T Tauri, obtained by Brown et al. (1984) with IUE. Apart from the lines of Mg II, C II] and Al II], most of the other lines are due to Fe II. Figure 2 gives a partial term diagram for Fe II, to illustrate some transitions and excitation processes discussed below.

The processes populating the excited levels and metastable levels in Fe II have been discussed by a number of authors in various astrophysical contexts (see references in Jordan 1988b). In particular, Viotti (1976) produced a useful form of diagram to show the relative importance of photoexcitation by the
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Fig. 1. Multiplets of Fe II in the spectrum of the pre-main-sequence star T Tauri, obtained with IUE by Brown, Ferraz & Jordan (1984).

Fig. 2. Partial term diagram for Fe II showing levels populated by ion-electron collisions (c), by photospheric radiation (d), and by H Ly α (e), in cool giants. Some examples of decay routes are indicated. Optically thick permitted lines between groups a, b, and c, d transfer photons to intersystem lines.

Example terms
(a) 4s ⁵D
(b) (a ³F) 4s b ⁴F
(c) (⁵D)4p ⁶D₀
(d) (⁵D)4p ⁴F₀
(e) (⁵D)5p ⁴F₀
(f) 5s e ⁴D
optical continuum radiation in hot stars and collisional excitation. The same type of approach can be used for cool stars (Jordan 1988b, Judge, Jordan & Feldman 1992) (see below also).

Two other processes are also important in cool stars (see Figures 1 and 2). First, many of the permitted lines to the ground term and low lying metastable terms have high optical depths. Photons can then be transferred to lines which are spin forbidden, or otherwise have small oscillator strengths, and which share a common upper level with the optically thick lines. For example, in late-type stars this process enhances the strength of multiplets uv 32, 33, and 34, and multiplets uv 60 and 61 at the expense of multiplets uv 1, 2, and 3. The resulting line ratios can then be used to measure the optical depth in the optically thick lines (Jordan 1967, Brown et al. 1984). Secondly, the strong H Ly α line in late-type stars can excite levels around 10 eV above the ground state, resulting in fluorescent lines in Fe II, for example in uv 391 and 399 (Johansson & Jordan 1984). The importance of these processes in the M supergiants is illustrated by the spectra shown in Figure 3, which shows the fluorescent lines in uv 380, 391, and 399 and multiplet uv 61 which is pumped by the optically thick multiplet uv 3.

It is clear that a large number of oscillator strengths (or transition probabilities) are required to interpret the lines formed by the above two radiative processes. Calculations using semiempirical methods, taking into account configuration interaction and intermediate coupling have been carried out by Kurucz (1981, 1988, the latter being available on tape) and by Fawcett (1987). Compilations of experimental f-values are also available (Fuhr, Martin & Wiese 1988). More recently, Nahar & Pradhan (1994) have
published some f-values resulting from the Opacity Project (Seaton 1987). The calculations were made in the close coupling approximation using the R-matrix method and adopting the LS coupling scheme (although the use of observed energy levels introduces some allowance for relativistic effects). Results for some 36,000 transitions were obtained. Comparisons are made, for selected permitted multiplets, with the calculations of Kurucz (1988) and the experimental data in Fuhr et al. (1988) and later papers. Although in the majority of cases the new f-values agree with those of Kurucz to within 10%, Nahar & Pradhan (1994) conclude that overall their results agree better with the experimental results. In general the results of Nahar & Pradhan (1994) agree more closely with those of Kurucz (1988) than with those of Fawcett (1987). Although the Opacity Project results are to be preferred for permitted transitions, the calculations by Kurucz (1988) are more useful for the interpretation of solar and stellar uv spectra because of the treatment of spin forbidden lines.

Ekberg & Feldman (1993) have used observations of the solar emission line spectrum above the limb to deduce the f-values of lines observed. They assume that all levels have a Boltzmann population (up to 10.5 eV above the ground), and take no account of the photon transfer and H Lyα pumping discussed above, although they recognize that the former occurs. The effects of photon transfer are obvious in the variation of “apparent” f-value with height above the limb. Although some multiplets give f-values close to the experimental values, others are substantially different, which is not surprising in view of the approximations made. More sophisticated calculations of the line formation are required to make a detailed comparison with these solar data.

The relative importance of excitation by ion-electron collisions and optical continuum radiation in late-type giant stars has been discussed by Judge, Jordan & Feldman (1992). Provided a line is effectively optically thin, the line flux can be used to find the emission measure. Estimates show that the even parity levels up to at least 5 eV will have a Boltzmann population at the local electron temperature. The population of the upper level of a transition can be expressed in terms of the total collision strength, Ω_u* (allowing for excitation from a number of lower levels and the major decays from the upper level, including those affected by radiation transfer), and the partition function, Z. For the stars considered by Judge et al. (1992), the emission measure distribution is known from lines of other species. Thus by plotting the emission measure derived from each Fe II multiplet as a function of temperature using an arbitrary value of Ω_u*/Z = 0.1, the effective value of Ω_u* can be found at a chosen temperature. Although comparisons were made with theoretical collision strengths, the primary aim was to examine excitation mechanisms. If the same effective collision strength is found for several stars with different photospheric temperatures, then the formation of the multiplet is likely to be dominated by ion-electron collisions. This is the case for emission from the excited terms z 6D0 and z 6F0. However, the effective collision strengths for the terms z 6Po, z 4D0, z 4F0, and z 4Po differ from star to star, and are larger than...
any of the theoretical values. Calculations of the level populations using preliminary collision strengths by Berrington & Pradhan in LS coupling (private communication 1991; see also Pradhan & Berrington 1993) and a simple treatment of the radiative transfer were made and showed that these terms are mainly excited by the photospheric radiation field. Thus in the giant stars, summing the Fe II uv line fluxes to estimate the chromospheric radiation losses will give an overestimate, in fact by more than a factor of 2. However, a plot of photospheric temperature against $N_e(T_e/10^4)^{-1/2}$, as used by Viotti (1976) (see Figure 9, Judge et al. 1992), shows that in the late-type dwarf stars essentially all the uv Fe II emission arises from ion-electron collisions so that the emission represents a real energy loss.

At present selected line ratios can be used to estimate line opacities and the Boltzmann temperature describing the population of the low lying levels. To make full use of the solar and stellar Fe II spectra will require further collision strengths, including those for the most important spin forbidden transitions. Because some members of multiplets are blended, or occur where the continuum is strong, the calculations and analysis need to be made for the fine structure components. Further effective collision strengths are expected from the work of Pradhan & Berrington and in the longer term results from the new Iron Project should be very useful.

2.2 Other Species

Three other species for which further atomic data are required are now mentioned briefly. The first is S I, which gives rise to lines in a number of multiplets observed in the short wavelength IUE spectra of cool low gravity stars, as well as in the solar spectrum, where weaker lines can be observed. Judge (1988) carried out a comprehensive study of S I in stellar spectra, and showed that a variety of collisional, recombination, and fluorescent processes were operating. He discusses the large amount of atomic data required in his calculations and points out the need for photoionization cross-sections from the ground configuration metastable levels, and oscillator strengths involved in the excitation and decay of the high n levels pumped by H Lyman $\alpha$. S I is also important in the context of Io and the Io torus and there have been recent new measurements of oscillator strengths required for the interpretation of these spectra (Doering 1990, Beideck et al. 1994), as well as further calculations of the photoionization from the ground term (Mendoza & Zeippen 1988, Altun 1992). Any further results for S I from the Opacity Project would be of interest.

The new results for Fe I from the Opacity Project could be applied to the fluorescent excitation of Fe I (uv 44) by the Mg II k line, discussed by Harper (1990). Harper points out that because Fe I is the minority species where the fluorescent excitation takes place, his results are sensitive to the rates used in finding the ionization equilibrium, in particular to the relative photoionization cross sections from the Fe I levels and the calculated continuum radiation, which depends on the continuous opacity. There is also some sensitivity to the oscillator strengths adopted. Harper (1990) demonstrated that the Fe I emission lines are formed in the chromospheres of the giants and
bright giants considered, and that they provide valuable constraints on chromospheric models. Future calculations for these lines will clearly benefit from the new results presented by Sawey & Berrington (1992).

The third ion of interest is Fe III. Forbidden lines of Fe III were discovered in the solar uv spectrum by Jordan et al. (1986). The transitions are between the 3d^6 a^5D ground term and the 3d^54s a^5G, a^5P, and b^5D terms, and are magnetic dipole and/or electric quadrupole transitions. The lines are not strong and occur at the limb in a coronal hole. Jordan et al. (1986) used rough estimates of the atomic data to show that the lines might have potential for measuring N_e at temperatures around 2 to 3 x 10^4 K, and pointed out the need for transition probabilities and collision strengths for the levels concerned, which are not included in existing calculations by Berrington et al. (1991). According to the review by Pradhan (1994), extensive calculations are now in progress. Since there are no other methods of measuring N_e in the low transition region, the outcome of these calculations is awaited with interest.

3. Coronal Spectra

The spectrum of the solar corona is well observed and there have been concerted efforts to improve the collision strengths required for the interpretation of line fluxes. The existing data have been reviewed as part of the preparations for the SOHO mission (see papers in the special volume edited by Lang 1994). Lines of highly ionized iron dominate in the wavelength range below about 400 Å, although the He I-like and H I-like ions are also important contributors below about 20 Å. The relative number densities of the various ions are an important factor in interpreting the line fluxes and in the radiative power loss codes used to interpret lower resolution stellar coronal spectra. Some comparisons of published ion populations are made below, since the commonly used codes have adopted different sets of calculations. Although the codes are being revised, there are many analyses in the literature that have used the existing or previous versions, so it is important to examine these differences.

3.1 The Relative Populations of Fe Ions

In their original paper Raymond & Smith (1977) used ionization rates by Summers (1974a,b), based on the Exchange Classical Impact Parameter (ECIP) approximation. Later comparisons with experimental data showed that for ionization from ground states these ECIP rates needed to be revised upwards by about a factor of two (Burgess & Chidichimo 1983), resulting in values that are similar to those from the formulae of Seaton (1964) (over the appropriate energy range) and Lotz (1967). Ionization via collisions to autoionizing states was also included following Summers (1974a,b). The dielectronic recombination rates were calculated from the general formula of Burgess (1965), without the correction for additional decays to the recombining ion via autoionization, proposed by Jacobs et al. (1977). The current code (see Raymond 1988) (i.e., prior to the inclusion of the revised calculations by Arnaud & Raymond 1992), uses the ionization rates of Younger (1983), plus excitation-autoionization rates
based on Cowan & Mann (1979) and for dielectric recombination uses the correction to the Burgess (1965) general formula proposed by Smith et al. (1985). Raymond (1988) gives more details and makes some comparisons between different sets of ion balance calculations and power loss codes available at that time.

The codes developed by Mewe and colleagues (Mewe, Gronenschild & van den Oord 1985, Kaastra 1992) make use of the ion balance calculations by Arnaud & Rothenflug (1985). The latter authors discuss in detail the rates used for each isoelectronic sequence, but for the ions of Fe discussed here they use direct ionization rates from Younger (1982, 1983) and excitation-autoionization rates from the method of Sampson (1982). Taken together they find that their rates are similar to those given by the Lotz (1967) formula, except where the excitation-autoionization rate is dominant. Thus the ionization rates used in the Mewe/Kaastra (MK) code are similar to those used in the Raymond-Smith (RS) code. However, Arnaud & Rothenflug (1985) use the dielectric recombination rates of Jacobs et al. (1977) for Fe, which for ions above about Fe XV are significantly smaller than those from the Burgess (1965) general formula because of inclusion of additional routes for autoionization in the recombing ion. As others have pointed out (see review by Hahn 1985), the reductions proposed by Jacobs et al. (1977) appear to be too large. Thus the calculations by Arnaud & Rothenflug (1985) would be expected to give lower temperatures for the peak ion fractions than found in the RS code, in particular for ions above Fe XV. This is indeed the case for Fe XVI to XXI, but for higher ions the results are very similar. For Fe XVII to XXI the peak ion populations in the RS code are slightly lower than those in the MK (or LMF) codes, but are similar for higher ions. For Fe IX to XIV the RS ion fractions peak at similar or lower temperatures than do those of Arnaud & Rothenflug (1985), and the peak ion fractions are similar or slightly higher.

More recently Arnaud & Raymond (1992) have made a detailed study of the ionization and recombination rates for the Fe ions. The direct ionization rates are still based on the parametric formula of Younger (1981), but the excitation-autoionization rates and dielectric recombination rates are discussed for individual ions, in the context of experimental results. The comparisons made by Arnaud & Raymond (1992) between their ion fractions and those of Arnaud & Rothenflug (1985) show significant differences for a number of ions, in particular Fe IX. In Fe X to Fe XIV the differences apparently arise mainly from the lower dielectric recombination rates used by Arnaud & Raymond (1992), but for Fe X to Fe XVII the new results do not differ significantly from those used previously in the RS code. In Fe XVIII to XXIV, the new peak temperatures are higher than in either the Arnaud & Rothenflug (1985) or the RS code calculations, because of the higher dielectric recombination rates used by Arnaud & Raymond (1992).

Landini & Monsignori Fossi (1990) (LMF) have adopted the expressions and fitting coefficients given by Shull & van Steenberg (1982a) for direct ionization, and radiative and dielectric recombination, and have corrected several typographical errors in addition to the error pointed out by Shull &
Fig. 4. Ion populations for (a) Fe IX and (b) Fe XIII. Full line - Arnaud & Raymond (1992); dashed line - Arnaud & Rothenflug (1985), dotted line - Jordan (1969); dash-dot line - LMF code; double dash-dot line - RS code.

van Steenberg (1982b). They use excitation-autoionization rates from Arnaud & Rothenflug (1985). As LMF point out, their results are significantly different from those of Shull & van Steenberg (1982a) for Fe XVI, Fe XVII, Fe XXV, and XXVI. However, there are also large differences for Fe XIII and Fe XIV. Since the results are sufficiently different overall it is best to regard the ion populations in LMF as independent calculations, rather than as an adoption of those by Shull & van Steenberg. Although for most ions (except Fe IX) the peak ion populations and temperatures found by LMF lie between those of Arnaud & Rothenflug (1985) and those of Arnaud & Raymond (1992) or of Jordan (1969, 1970), the distributions tend to cover a narrower range of temperature at a given value of $N_{\text{ion}}/N_E$.

Because of the revisions (both upwards and downwards) of the various rates in recent years, it is of interest to compare also with the earlier calculations by Jordan (1969, 1970). These used the Seaton (1964) formula for direct ionization (which becomes inaccurate at high temperatures for a given ion), and a detailed treatment of the excitation-autoionization rates, albeit with approximate excitation rates. In the "low" density set of calculations the general formula of Burgess (1965) was used for dielectronic recombination. For Fe X to Fe XV the temperatures of the peak ion fractions tend to be largest in the calculations by Jordan (1969). Direct comparisons can be made between the ionization and recombination rates used in the RS code and those of Jordan (1969, 1970); (the rates for Fe XVII to Fe XXVI are published in Jordan 1970).
For Fe IX to Fe XIV, near the temperatures of the peak ion populations, the ionization rates used by Jordan (1969) are on average only 0.09 dex smaller than those used by RS. For Fe XVII to Fe XXIII the difference is only 0.07 dex, in the same direction. The results for other ions are also similar, except for Fe XVI, which has a large excitation-autoionization rate, where the rate used by Jordan is a factor of 1.8 larger than that of RS. Since Jordan (1969, 1970) used the Burgess (1965) dielectronic recombination rate while RS use the corrections proposed by Smith et al. (1985), one would expect the rates used by Jordan to be larger. Where there are differences this is generally the case. For Fe IX to Fe XIV the rates used by Jordan (1969) are on average (near the peak of the ion population) 0.24 dex larger, resulting in higher peak temperatures. Although there are systematic differences, for Fe X to Fe XIV (ignoring the very different results in Shull & van Steenberg 1982a), the peak ion fractions from all three calculations (Arnaud & Raymond 1992, Arnaud & Rothenflug 1985, Jordan 1969) agree to within about 0.10 dex, and the temperatures for the peak ion fractions differ by less than about 0.10 dex (see e.g., Fe XIII in Figure 4b). As discussed by Arnaud & Raymond (1992), there is a larger difference between the sets of calculations for Fe IX (see Figure 4a). Figures 5a and 5b show the different calculations for Fe XV and Fe XVI, since these ions produce strong lines in EUVE spectra of cool stars. For Fe XVII to Fe XXIII the difference between the dielectronic recombination rates used by Jordan (1970) and Arnaud & Raymond (1992) is on average only +0.18 dex. For Fe XVII to Fe XXVI there is remarkably good agreement between the calculations by Arnaud & Raymond (1992) and those by Jordan (1970) (see Figures 6a and 6b, which show the results for Fe XVII and Fe XVIII). Since the ionization rates used by Arnaud & Raymond (1992) for these ions have not changed significantly from those in the RS calculations, which, as discussed above, are only 0.07 dex larger than those used by Jordan (1970), one concludes that the dielectronic recombination rates now
Fig. 6. Ion populations for (a) Fe XVII and (b) Fe XVIII. Symbols, see Figure 4, but dotted line here is Jordan (1970).

used by Arnaud & Raymond (1992) are very similar to those calculated by Jordan (1970). Thus the results of Arnaud & Raymond (1992) agree with those of Jordan (1970) because essentially the same rates are used.

At present there are no published sets of ion balance calculations as a function of $N_e$, which use up to date ionization and recombination rates. Jordan (1969) made approximate estimates of the reduction of the dielectronic recombination rates under solar conditions, but the work by Summers (1974a,b) showed that these overestimated the effects. The density dependent ion populations calculated by Summers (1974a,b) used ECIP ionization rates that are now regarded as being too small.

4. Other Comparisons of Power Loss Codes

The rates used to calculate the ion fractions in the RS, LMF, and MK codes (versions up to August 1994), and the resulting differences in the peak ion populations and temperatures have been discussed above. The other important aspects are the number of transitions treated, whether they are treated by multiplet or as individual lines, the collisional excitation rates adopted, and the element abundances used. All three codes use cosmic abundances from Allen (1973); these can easily be changed if desired. Detailed comparisons of collision strengths are beyond the scope of this review and the original papers should be consulted.
Mewe et al. (1985) list 2167 lines between 1.29 and 296.1 Å, giving parameters from which the excitation rates used can be derived. Landini & Monsignori Fossi (1990) say that they have made calculations for over 1000 lines, but in their recent paper (Monsignori Fossi & Landini 1994) they refer to over 2000 lines in the earlier paper. Since they extend the wavelength range to 2000 Å and list about 300 lines above 296 Å, they appear to include fewer individual lines than in the MK code in the overlapping wavelength range below 296 Å. The RS code includes about 1100 lines below 1000 Å. A brief comparison between the lists shows that the RS and LMF codes treat some transitions by multiplet rather than by individual lines, and that the RS code is crudest in that it treats some multiplets from a given type of transition (e.g. 3p - 3d) as a single line. Since 1990 Monsignori Fossi & Landini have improved their treatment of the strong lines of iron between 170 and 300 Å, and this version has been available from the authors. Thus of the “current” codes, the MK code appears to include the largest number of individual lines below 296 Å, and the LMF code includes more individual transitions than the RS code.

Some types of transitions are still not included in the codes, or are treated only approximately. For example, transitions of the type 3p^n - 3p^{n-1} 4s, 4p, 4d, and 4f in Fe IX to Fe XIV, 3s^n - 3s^{n-1} 4s, 4p, and 4d in Fe XV and Fe XVI, and 2p^n - 2p^{n-1} 3p, in Fe XVII to Fe XXII. The treatments of Fe XV, Fe XVI, and Fe XVII are the most complete (see Mewe et al. 1985), but the excitation rates used are often based on simple approximations. However, more accurate rates are available for several isoelectronic sequences from the work of Sampson, Zhang & Fontes (1990, 1991), Zhang & Sampson (1989), and Zhang, Sampson & Fontes (1990). Some years ago Jordan (1968) pointed out that groups of unidentified lines in the solar spectrum between 70 and 170 Å might be due to decays from the 3p^{n-1} 4f and 3p^{n-1} 4p levels in Fe IX to Fe XIV, whose wavelengths were not known in detail at that time. Subsequent laboratory and theoretical work (e.g., Fawcett et al. 1972, Fawcett 1974) has improved the situation and known transitions are listed in Kelly (1987). Some of the transitions can be identified in the solar spectrum (see, e.g., Fawcett 1974). Although the lines are not strong and add only about 10% to the strength of the 3p - 3d transitions (Jordan 1968), the decays will contribute to the background of weak lines. Similarly, at shorter wavelengths the decays from the 2p^{n-1} 3p levels will contribute to the strength of the 2p^{n-1} 3s to 2p^n transitions.

The differences between the codes show up when they are applied to the interpretation of low resolution X-ray spectra. Pan & Jordan (1994) have made two temperature fits to ROSAT PSPC spectra of CC Eri, a K7 Ve star with flaring activity, using both the RS and LMF codes. Figure 7 shows the ratio of the higher temperature emission measures (LMF/RS) as a function of the higher temperatures of the 2T fits. These values depend on the atomic models and collision strengths, as well as the ion populations, of ions formed between about 2 x 10^6 K (the temperature of the lower component, T_1) to 1.1 x 10^7 K, so that it is difficult to identify a single cause of the differences. However, it appears that the differences do not lie only in the ion populations. The RS code leads to larger emission measures at T_1, but smaller emission measures at the higher temperature, T_2, than does the LMF code, and gives higher values of T_2.
Fig. 7 Ratio of emission measures found using two-temperature fits to ROSAT PSPC spectra of CC Eri (K7 Ve), and the LMF and RS codes. $E_m(V)_2$ and $T_2$ refer to the higher temperatures. Triangles - $T_2$ from the LMF code; circles - $T_2$ from the RS code. From Pan & Jordan (1994).

Spectra of $\xi$ Boo A + B (G8 V + K4 V) obtained with EUVE, which show lines of Fe XV, XVI, and XVIII, have been analyzed using the ion populations calculated by Arnaud & Raymond (1992), Arnaud & Rothenflug (1985), Jordan (1969, 1970) and those in the LMF code, with collision strengths recommended by Badnell & Moores (1994). The emission measures found using the ion populations of Arnaud & Raymond (1992) lead to the most self-consistent emission measure distribution between $2 \times 10^6$ K and $6 \times 10^6$ K. The lower peak ion population for Fe XVI in the LMF code and in Arnaud & Rothenflug (1985) leads to an emission measure for Fe XVI which cannot be fitted simultaneously with that of Fe XV. Emission measures from upper limits to the EUVE fluxes in lines of lower stages of ionization can be compared with those from single temperature, two temperature and continuous emission measure fits to our ROSAT PSPC spectra. All of the emission measures corresponding to the lower temperatures of the 2T fits are nearly an order of magnitude larger than the upper limits imposed by the EUVE spectra. The continuous emission measure fits and the emission measures corresponding to the higher temperature of the 2T fits give acceptable results. One should therefore beware of interpreting 2 T fits to the PSPC data. A paper giving details of the above analyses is in preparation (Jordan et al. 1994).
There have been further developments since this paper was given. Monsignori Fossi & Landini (1994) have recently adopted the ion populations of Arnaud & Raymond (1992), and have used some improved collision strengths from the assessment exercise for SOHO (Lang 1994). Similarly, Brickhouse, Raymond & Smith (1994) have improved the treatment of the strong lines of Fe IX to Fe XXIV in the RS code, but do not include the cascades following transitions with $\Delta n = 1$ except in Fe XVII.

5. Conclusions

It has been possible to give only a few examples of how the analysis of stellar chromospheric and coronal spectra depend crucially on a very large amount of atomic data. In addition to the opacity projects, preparations for the analysis of spectra to be obtained with the CDS and SUMER instruments on SOHO have stimulated new work which will be more widely applicable. Recent work on ion populations has concentrated on iron, but similar revisions may be needed for other elements. Although the "current" emissivity codes are not entirely satisfactory in various respects a number of improvements have been made recently. These have in part been stimulated by the line spectra obtained with EUVE, which allow the detailed predictions of the codes to be tested.

Acknowledgments

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References

Doering, J. P. 1990, J. Geophys. Res., 95, 21313
Fawcett, B. C. 1987, Atomic Data Nucl. Data, 37, 333
Kurucz, R. L. 1988, private communication
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Seaton, M. J. 1964, Planet. Space Sci., 12, 55
Summers, H. P. 1974b, Appleton Laboratory Report, AL-R-5

Discussion

Linsky: Would you comment on the accuracy with which one can determine coronal electron densities with the rather low signal/noise EUVE spectra? For example, very large electron densities have been derived from EUVE spectra of Capella by Dupree et al. (1993).

Jordan: While I agree with the identifications of the stronger lines in Capella given by Dupree et al. (1993), I am less convinced by the identifications of the very weak lines which appear only when \( N_e \) has a large abundance. These weak lines are comparable in intensity to the noise level. I think that further exposures are needed to confirm that they are present. I, therefore, regard the high densities deduced as not yet proven!

Mewe: Just a comment on the comparison you made for the derived emission measure ratios on the dependence of temperature from ROSAT observations. The Raymond-Smith (RS) results give much higher temperature than the Landini and Monsignori Fossi (LMF) value. I expect that our code would give results close to LMF because the ionization balance we used is quite similar (Arnaud & Rothenflug, Shull & van Steenberg) and is very different from the RS ionization balance which I would not trust too much. On the contrary, using
the new Arnaud & Raymond calculations probably gives a significant improvement, at least for the Ne isoelectronic sequence. Concerning Linsky's problem about the accuracy of the electron number density from ratios of highly ionized iron lines in the EUVE Capella spectrum, I would like to say, that this may be estimated to be only about a factor of five.

Jordan: The differences between the codes vary according to which ions are being considered. For the ROSAT spectra of CC Eri, the Kaastra code gives temperatures higher than those found using the LMF code, and only a little lower than found using the RS code, but factors other than the ion populations enter this comparison. For Fe XVI to Fe XXI the peak temperatures found by Arnaud and Rothenflug are slightly lower than those found from the RS code or the LMF code, but for higher ions the results are very similar.