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The spectra of cool stars in the ultraviolet region

ABSTRACT

The spectra of cool stars in the wavelength region from 1200 Å to 3000 Å are now well known after eleven years of operation of the International Ultraviolet Explorer (IUE). The solar spectrum provides a detailed guide to the spectra of other main sequence stars from type ~ F5 V to M5 V. Photo-excitation processes become relatively more important in cool giants and supergiants and control much of the emergent spectrum in low gravity stars cooler than ~ K1. Photo-ionization cross-sections and oscillator strengths are required in the interpretation of these spectra.

INTRODUCTION

Observations from rockets and space vehicles have provided a wealth of detail about the solar uv and X-ray spectrum. (See reviews by Tousey, 1988; Feldman, Doschek and Seely, 1988; and Jordan, 1988). Apart from a few lines, the emission from ionized species is controlled predominantly by collisional excitation by electrons. Emission from neutral lines can also be the result of radiative recombination. A full line list for the region 1175 Å ~ 1710 Å can be found in Sandlin et al. (1986).

The IUE satellite, which has now operated successfully for over 11 years, has led to a substantial amount of information concerning the spectra of other late-type stars, in the wavelength region from ~ 1200 Å to 3000 Å. It has become clear that the uv spectra of main-sequence (dwarf) stars, later than ~ F5 V, are very similar to the solar spectrum, although differences in the structure of the chromosphere and transition region lead to changes in relative line intensities.

On the other hand, there are distinct differences between the solar spectrum and the spectra of giants and supergiants. The late F and type G to KO III giants still show emission from lines formed in a 'transition region', at temperatures between ~ 2x10^4 and 2x10^5 K, but emission in the 0 I resonance lines around 1304 Å is relatively stronger. Figure 1 shows a low resolution IUE spectrum of β Cet (G9.5 III), illustrating typical transition region lines and the strong 0 I resonance lines. (From Eriksson et al., 1983). This strong 0 I emission was discovered from rocket spectra of α Boo (K2 III) (McKinney et al., 1976) and is caused by fluorescent excitation of the 3d 3D^o term in 0 I by the strong H Ly β line at 1025.72 Å. (Haish et al. 1977). Observations with IUE have shown that this process is occurring in virtually all cool low gravity stars.

Giant and supergiant stars cooler than K I III or mid-G I have spectra which below ~ 2000 Å are dominated by radiative processes, with lines excited by ion-electron collisions being relatively weaker. Since most of the requirements for further atomic data arise from these observations of cool low gravity stars the rest of this review will concentrate on their spectra, and how they relate to the conditions in the stellar chromospheres. The potential use of future observations from space will be briefly mentioned.

UV SPECTRA OF COOL GIANTS AND SUPERGIANTS

In the IUE short-wavelength region, (SWR) ~ 1200 Å ~ 2000 Å, the spectra of cool giant stars (later than ~ K1 III) are dominated by H Ly α (1216 Å) and the 0 I resonance lines (uv 2) at ~ 1304 Å. Figure 2 shows a low resolution spectrum of β Cru (M5 III), taken from Johansson and Jordan (1984).

At high resolution (~ 0.07 Å), it becomes apparent that the blend at ~ 1816 Å contains both Si II (uv 1) and the three lines of S I (uv 2), and that the intensities of the S I lines increase relative to those of Si II as the surface temperature of the star decreases. (Brown and Jordan, 1980; Carpenter and Wing, 1979). The lines of Si II are excited by ion-electron collisions, but as discussed further below, the S I lines depend on the H Ly α radiation field and the consequences of high line opacities.

High resolution observations also show that the strong feature at ~ 1304 Å in the low resolution spectra is a blend of 0 I (uv 2) and of S I (uv 9). This is illustrated in Figure 3, which shows the lines in α Boo (K2 III), from Ayres et al.
Fig. 1. A low resolution IUE spectrum of β Cet (G9.5 III). From Eriksson et al. (1983).

Fig. 2. A low resolution IUE spectrum of β Cru (M5 III). From Johansson and Jordan (1984).

The O I lines, which are themselves excited via H Lyβ fluorescence, have two wavelength coincidences with members of S I uv 9, and cause the observed S I emission, again by fluorescence.

Of the remaining lines, only those of C II (uv 1) and Fe II originate from singly charged ions. The rest of the spectrum is made up of several multiplets of S I, lines of C I and further O I transitions. Also, weaker features which appear systematically in the cool giant spectra can be identified as lines of CO, in the fourth positive system, again excited by fluorescence by the strong O I resonance lines. (Ayres et al., 1981). High resolution observations (Ayres et al. 1986) suggest that the transitions are from excited V=9 levels to the lower V=1,2,5 and 9 levels, with the excitation by O I taking place in the O-9 band.

In the IUE long wavelength region (LWR), from ~ 2000 Å to 3000 Å, the Mg II resonance lines are usually the strongest feature. Inter-system lines of C II (uv 0.01), Si II (uv 0.01) and Al II are also present but the majority of the emission lines are from Fe II. Wing, Carpenter and Wahlgren (1983) have prepared a very useful atlas of high resolution IUE spectra from low gravity stars.

Many of the Fe II lines are from the strong resonance multiplets (uv 1 to 5) and from multiplets terminating on low lying even terms, (eg uv 35, 36, 62, 63, 64), and these are probably excited by ion-electron collisions. However, a number of multiplets are present which would not be strong without some additional source of excitation. Two types of process occur. First, multiplets which have low transition probabilities (eg uv 32-34, uv 60, 61 and uv 78) but which share a common upper level with a strong, optically thick multiplet have their intensity enhanced by 'line leakage' (Brown, Ferraz and Jordan, 1981). Secondly, the strong H Lyα line causes fluorescent excitation of levels around 10 eV, which decay through multiplets such as uv 380, 391 and 399 around 2800 Å to 2900 Å, and in transitions to a αP and c αF around 1289-1300 Å and 2507-2509 Å, respectively. (Johansson and Jordan, 1984). A number of other fluorescent routes exciting lines in Fe II, Cr II and Ni II have recently been discussed by Carpenter et al. (1988), in the context of γ Cru (M3.4 III).

Other fluorescent processes also lead to
lines observable in the LWR region. The most striking example is the excitation of the Fe I \(\gamma^5\)G\(^0\) J=3 level, from a \(2p^4\), by the Mg II (uv 1) line at 2795.5 Å, which produces two strong emission lines in Fe I at 2843.98 Å and 2832.28 Å (Gahm 1974; Van der Hucht et al., 1979). The lines are seen in a wide variety of giants and supergiants cooler than \(\sim 4500\) K.

At the sensitivity of IUE few well-resolved emission lines remain unidentified in the SWR spectra and the weaker lines or contributors to blends cannot be observed at high resolution. A relatively small number of weak lines remain unidentified in the high resolution LWR spectra, and these are likely to be due to transitions in singly charged ions. In the solar spectrum, apart from weak lines (see Sandlin et al. 1986), most lines of any strength have acceptable identifications, but there are a few exceptions. The first is at 1318.99 Å, and is usually attributed to N I (uv 12), but the line is significantly stronger than expected from the rest of the multiplet. The spatial behaviour of the line suggests a neutral atom is the origin and as Chilman and Bruner (1975) point out it behaves like the S I line at 1300.91 Å. This is a line from a level above the first ionization limit. Muller (1968) reports an unidentified line of S I at 1319.0 Å, and Berry et al. (1970) also list an unidentified line of S I at 1318.0 Å in their beam foil spectra. A re-examination of the S I spectrum in this region would be of value. A similar line appears at 1351.66 Å, and has been attributed to Cl I, photoexcited by the strong line of C II at 1335.17 Å (Shine, 1983). However the spatial behaviour of this line makes the identification dubious and it may also be from an unknown level above the first ionization limit in C I, S I or Si I. The line is also observed in the spectra of cool giants, which suggests that recombination might be the excitation mechanism.

**EXCITATION PROCESSES AND PLASMA DIAGNOSTICS**

The relative decrease in the importance of collisional excitation and increase in radiative excitation can be understood in terms of the lower surface gravities of cool giants and supergiants. The electron density is lower than in main-sequence stars or hotter giants, scaling roughly as \(T_\text{eff}^{1/2}\), while the opacity in strong lines increases roughly as \(T_\text{eff}^{-1/2}\) (Ayres, 1979), owing to the greater extent of the atmosphere in hydrostatic equilibrium. The fluorescent excitation processes are aided by the large opacities of the strong lines that cause the photoexcitation.

Judge (1986) has discussed the effects of the H Ly \(\alpha\) radiation on the photoionization of neutral species such as S I, from the \(3p^4~3d^2\) level; C I, from the \(2p^3~3d^2\) level; and of Si I, from the ground \(3p\) term. The radiation resulting from radiative recombination in C I also photoionizes S I (Judge, 1988). Although recent calculations are available for the photoionization cross sections of the ground states of S I and S I, (Mendoza and Zelippen, 1988), calculations of comparable accuracy are required for cross sections out of the excited terms of the ground configurations in C I and S I.

In S I the excitation by H Ly \(\alpha\) occurs to several high levels with \(n~12, 13\). But because of a strong series perturbation (with \(3p^3~3d^2\)), the oscillator strength for the most important excitation, in \(3p^4~3p^21d^2~3d^0\) is not well known. Also, the emergent spectrum depends on the transition probabilities for the decay routes and these too require further attention. (See Judge, 1988, for details). Judge concludes that the emission in S I uv 2 is produced by the H Ly \(\alpha\) excitation, but that emission in uv 1 and uv 3 is formed by radiative and low temperature di-electronic recombination, respectively. Improved values for the radiative and autoionizing decay rates for levels above the first ionization limit are thus also needed. In multiplet uv 1 the observed relative intensities of the two transitions from \(3p^34\) \(5s^0\) do not agree with the calculated branching ratio, but this could be due to opacity effects.

The fluorescent excitation of O I by H Ly \(\beta\) has been discussed by Skelton and Shine (1982), in the context of the solar atmosphere. They used an observed branching ratio for the decays from \(2p^33d^3\) \(3d^0\), (Christensen and Cunningham, 1978), and an experimental f-value from Brooks et al. (1977) for the pumping transition, \(2p^4\) \(3p^3\) \(2p^33d^3\) \(3d^0\). However, these values differ significantly from the results of the close-coupling calculations by Pradhan and Saraph (1977), and in view of the importance of the O I lines in understanding stellar chromospheres these differences need to be resolved. Work is in progress at Oxford (Monday, private communication), on calculating the O I fluorescence in cool, low gravity stars.

The first calculations of the excitation of the Fe I \(\gamma^5\)G\(^0\) level by the Mg II k line at 2795.5 Å have recently been made by Harper (1988, 1989) for \(i\) Aur (K3 II) and several
cool giants. He finds agreement between observed and calculated fluxes to within a factor of two, depending on the details of the models adopted. The Fe I lines are potentially a valuable diagnostic of the mid chromosphere in cool giants, between the regions where the Ca II H and K and Mg II h and k lines are predominantly formed. However, the fluorescence occurs where iron is mostly in the form of Fe II, and the results are sensitive to the Fe I/Fe ion population ratio. Further work on the relative photoionization cross sections from Fe I levels would be of value.

The f-value of the pumped transition is small and the y \(^{5}\)C\(_{4}\) level is strongly mixed with \(^{5}\)H\(_{7}\) (Fawcett, 1987), but Harper finds that the calculated line fluxes are more sensitive to the ion balance than this f-value.

Lines which are interlocked through a common upper level are particularly useful when one of the states is optically thick and the other is optically thin. Two cases occur in the IUE SWR spectra; C I (uv 2) at \(\lambda \sim 1656 \text{ Å}\), shares a common upper level with C I (uv 32), at 9306 Å. Mult. uv 2 is optically thick, while uv 32, 2p\(^{2}\) \(^{1}\)D\(_{2}\) + \(^{2}\)P\(_{3}\) \(^{0}\) \(_{1}\), being an intercombination line is optically thin. The ratio of the line fluxes then yields the optical depth, and hence the mass-column-density in uv 2. (Jordan, 1967). This is a valuable quantity when modelling stellar chromospheres and the method has been applied by Judge (1986) to \(\alpha\) Boo.

A similar pair of lines occurs in O I, where uv 146, at 1641.30 Å, is pumped by the resonance lines (uv 2). Multiplet uv 146, 2p\(^{2}\) \(^{1}\)D\(_{2}\) - 2p\(^{3}\)s \(^{3}\)S\(_{1}\), is a common feature in the spectra of cool low gravity stars (see Fig. 2) and the identification is confirmed by high resolution observations. (Brown and Jordan, 1980). The branching ratio from \(^{2}\)p\(^{3}\)s \(^{3}\)S\(_{1}\), has recently been calculated by Froese-Fischer (1987), since the 1641.30 Å line has also been discovered in day-glow spectra observed from satellites. The O I lines now provide a good method of determining the resonance line opacities. Other examples of this type are discussed by Jordan (1988).

Methods of determining the electron density directly from suitable line ratios, usually involving line system lines, are also important and many of the atomic data are now available. However, there remains a systematic discrepancy between calculated and observed line ratios within the Si II multiplet \(^{3}\)S\(_{2}\) \(^{3}\)P\(_{2}\) - \(^{3}\)S\(_{2}\) \(^{3}\)P\(_{1}\), around 2334–2350 Å. (Fig. 4). This occurs in both high density chromospheres, like the Sun, and in cool giants and bright giants (Judge, 1986; Harper 1988). The observed ratio of the transitions \(\left(\frac{^{4}\text{P}_{1} - ^{2}\text{P}_{2}}{^{4}\text{P}_{1} - ^{2}\text{P}_{1} / ^{2}\text{P}_{2}}\right)\) is lower than calculated and the observations suggest that the calculated branching ratio from \(^{4}\text{P}_{1}\) (Nussbaumer, 1977) is too large by an order of magnitude. Recent calculations by Huang (1987) give an even smaller ratio than required by the observations.

**FUTURE WORK**

The operation of the Hubble Space Telescope,
will provide data which, apart from some spectra obtained with Copernicus, have not been available for cool stars. The flux in the H Lyβ line and in members of the O I uv 4 multiplet, in which H Lyβ pumping occurs, would be directly observable. A considerable number of resonance lines occur in this region which will be of value in modelling the chromospheres and transition regions of late-type stars.

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