## SESSION 3. NON-SOLAR ASTROPHYSICS

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# ULTRAVIOLET SPECTROSCOPY OF COOL STARS FROM IUE

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## ABSTRACT

Observations of cool stars with the IUE satellite have shown that although main sequence stars have uv spectra similar to that of the sun, the spectra of the giants and supergiants are dominated by lines of neutral atoms and singly charged ions. The atmospheres of the low gravity stars are greatly extended and there is a large opacity in the stronger lines. This leads to multiple scattering and the appearance of many transitions through line 'leakage'.

A review is given of how high resolution IUE spectra have allowed line identifications to be established and some current problems are discussed.

The spectroscopic diagnostic techniques for the low gravity, low density atmospheres are also briefly outlined.

## INTRODUCTION

Over the past six years the International Ultraviolet Explorer Satellite (IUE) has allowed extensive observations to be made of a variety of cool stars. In the first few years of operation the observations of cool stars were usually obtained at low (~ 6 Å) resolution in order to survey the general properties of line fluxes from a wide variety of stars. As a result of this early work (see for example Linsky and Haisch, 1979; Brown, Jordan and Wilson, 1979; Dupree, 1982), it was found that main-sequence dwarfs and other relatively high gravity stars have spectra between 1200 Å and 2000 Å which show essentially the same emission lines as does the solar spectrum. (Above 2000 Å the appearance of emission lines rather than absorption lines depends on the effective temperature). Analyses of such spectra show that the density regime is within an order of magnitude or so of that in the solar atmosphere and that the majority of the emission lines arise through ion-electron collisions, as in the sun. There have, therefore, been no surprising developments related to the spectroscopy of these stars. The interest has lain mainly in the quantitative analyses of the spectra to find the structure and energy requirements of individual stars and in systematic correlations of line fluxes to investigate trends which might be related to the processes underlying the existence of hot coronae.

On the other hand, even an early spectrum of the cool giant, $\alpha$ Boo (K2 III) obtained from a rocket by McKinney, Moos and Giles (1976) showed that the emission lines from intermediate stages of ionization, formed up to $\sim 2 \times 10^5$K, which are common in the higher gravity stars are absent from the cool giants. Instead, lines from neutral atoms and singly charged ions dominate the spectra. Indeed, the spectrum obtained by McKinney et al. showed strong emission in the O I resonance lines around 1304 Å, which was accounted for by Haisch et al. (1977) in terms of fluorescence with H Ly $\beta$, following an early proposal by Bowen (1947). The IUE spectra



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have now shown that such strong O I emission is a common feature of cool giants and supergiants. Also, more recent work, particularly using high resolution spectra, has shown that accidental fluorescent processes and photo-excitation and line-leakage through interlocked lines play a very important role in producing the observed spectra. (See review by Jordan and Judge, 1984). Collisional excitation is less important than in the sun, but is still relevant in the initial production of photons, though the stellar surface fluxes may be lower because of the reduced electron temperatures.

The low gravity stars are found to have electron densities $\lesssim 2\times10^8 cm^{-3}$ (Stencel et al. 1981) and the spectroscopic diagnostic techniques developed for solar work are not appropriate. Instead new techniques become available. Although other low density objects such as planetary nebulae are reviewed elsewhere in these proceedings by Seaton, they are of interest also to stellar work through the limiting values they provide on line ratios. The ultraviolet emission line spectra of peculiar objects, such as that of the slow nova RR Tel (Penston et al. 1983) also have great potential for spectroscopic studies.

The sections below discuss recent work on line identifications, excitation mechanisms and spectroscopic diagnostic techniques and point out some areas where further work is required.

## LINE IDENTIFICATIONS

When spectra of cool giants and supergiants were first obtained at low resolution with IUE it was found that although most high temperature lines were absent a feature still appeared at around 1640 Å, where He II Bα is expected and observed in the dwarf stars. Blending with Fe II was a possibility but it was not until high resolution spectra of α Tau (K5 III) and β Gru (M3 II) were obtained (Brown and Jordan, 1980) that the wavelength of the additional line (1641.3 Å) could be measured. Both S I and O I have semiforbidden lines close to this wavelength, sharing common upper levels with strong optically thick multiplets. Given the strength of the O I multiplet at 1304 Å, the O I identification, $2p^3 3s\ ^3S_1{}^o \rightarrow 2p^4\ ^1D_2$ seems the more likely (Brown, Ferraz and Jordan, 1981). Also, as discussed below the relevant upper level in S I has an alternative decay route. Other examples of line leakage in semiforbidden lines sharing common upper levels with very optically thick multiplets occur in C I producing lines at 1993.6 Å (Jordan, 1967) and perhaps 1537 Å (Jordan and Judge, 1984).

The high resolution spectra of cool giants and supergiants also allowed various sets of close blends to be resolved. Carpenter and Wing (1979) found that in α Ori (M2 Iab) the feature which appears at ~ 1814 Å at low resolution is composed both of Si II (mult. uv 1) and of S I (uv 2) and that the S I lines are stronger. Both multiplets are present in the K giants but there the Si II multiplet dominates. The contribution of S I to the blend can be detected at low resolution and probably accounts for the apparently anomalous ratio between the Si II 1808 Å and 1816, 1817 Å components which was noted early in the IUE mission (Linsky et al. 1978).

Examples of accidental fluorescence have also been found through high resolution observations. This type of process has been known for some time to be important in the production of emission lines in the near uv and optical spectrum of cool stars. Gahm (1974) gave an extensive finding list for fluorescent lines excited by the strong lines of H I, Mg II and Ca II, the majority of which were for $\gtrsim$ 2000 Å. The most striking example of fluorescence by Mg II is the excitation of Fe I (mult. 44) which was observed prior to IUE with the BUSS spectrograph (Van der Hucht et al. 1979) and has since been seen in other K and M low gravity stars.

As mentioned in the Introduction the excitation of the O I resonance lines by cascades, following a fluorescent excitation by H Ly $\beta$ to a higher level, is now well-known. Early low resolution IUE spectra showed the presence of a blend to the short wavelength side of the O I multiplet (~ 1304 Å). The identification of this feature, suspected to be due to either S I or Fe II, was made through high resolution observations of $\alpha$ Tau and $\beta$ Gru (Brown and Jordan, 1980) which showed clearly that S I was the origin. Moreover, it was found that two members of the S I (mult uv 9) coincide with the broad O I lines at 1302 Å and 1306 Å. The member of the multiplet which cannot be pumped by O I is absent, showing the importance of O I in the excitation. Thus photons originating in H Ly $\beta$ escape eventually in both O I and S I.

One motivation for the high resolution observations of cool giants and supergiants has been to identify features present at low resolution where the poor wavelength accuracy and blending prevents unambiguous identification. From early spectra of $\alpha$ Tau and $\alpha$ Cet (MO III) Brown, Jordan and Wilson (1979) suggested that lines of Fe II excited by H Ly $\alpha$ and the O I (1304 Å) lines might be present. Later work has shown other identifications for some of these features (eg the S I, O I lines discussed above) but a recent long exposure of $\beta$ Gru (obtained in collaboration with Engvold and Stencel) shows some of the lines of Fe II as well (Johansson and Jordan, 1984). The upper levels of the observed lines are odd levels around 10 ev (levels of the 5p $^4D^o$, $^4F^o$, $^4P^o$, $^6F^o$ and 4p $^4P^o$, $^4G^o$ and $^4S^o$ terms) and are excited from a $^4D$ by Ly $\alpha$ photons. There are observed decays to a $^4P$ between 1291 Å and 1300 Å, perhaps to a $^4D$ around 1209 Å and 1220 Å, and to c$^4F$ at 2506.7 Å and 2508.30 Å. These latter lines are observed also in $\alpha$ Tau and in the spectrum of the slow nova RR Tel. (Penston et al. 1983). In a wider investigation of Fe II Johansson has identified a new $^4G^o$ level at around 107700 cm$^{-1}$ above the ground which can be pumped by H Ly $\alpha$ from the a $^4G$ levels and which accounts for quite strong emission lines in cool stars around 1870 Å at low resolution (Johansson and Jordan, 1984). This identification is particularly important since in stars such as $\alpha$ Ori H Ly $\alpha$ is not itself observable owing to extensive scattering and interstellar absorption. In general the pumping by H Ly $\alpha$ to the 10 ev levels can explain the strength of multiplets such as uv 399, 373, 380, 391, etc. which decay from them, and the absence of uv 402, 375 etc., which decay from slightly higher levels.

Johansson (1983) has identified further lines of Fe II in the uv spectrum of RR Tel, which are pumped by the strong C IV lines, and infra-red decays from the same upper levels in the spectrum of V1016 Cyg. The uv

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lines were identified in V 1016 Cyg by Nussbaumer and Schild (1981).

Mult. uv 191 of Fe II (at 1785 - 1788 Å) is proving to be of particular interest. This is a strong multiplet in a wide range of objects. Photoexcitation by continuum radiation at $\lambda \sim 1260$ Å has been suggested in systems including early type stars (eg Hagen et al. 1980, Stalio and Selvelli, 1980), photo-excitation by Si II (uv 4) at 1260.42 A via Fe II (uv 9) has been proposed by Viotti et al. (1980) but collisional excitation in the uv 191 itself was preferred by Nussbaumer et al. (1981) on the basis of the unfavourable branching ratio from the 1260 Å to the 1786 Å multiplets. The continuum photo-excitation process is favoured by Engvold, Jensen and Moe (1983). Johansson (1984) notes that recombination could be important in some objects. However, as Penston et al. (1983) point out it may also be significant that the upper term, x $^6P^o$, lies very close in energy to the e $^4D$ levels which are heavily populated by the cascades from levels excited by H Ly $\alpha$ and collisional population transfer could occur.

There are features in cool star spectra between 1200 Å and 2000 Å, some of which correspond to lines in the solar spectrum, which do not yet have a satisfactory identification. Given the dominance of radiative processes it is likely that they are transitions in neutral atoms or first ions which have levels which can be pumped by the strong lines of hydrogen or of O I. However, the upper levels may be rather high or be above the first ionization limit and further laboratory studies of such levels would be of value. Although coincidences with known lines can be found no satisfactory explanation emerges. The strongest lines are at 1347.08 ± 0.15 Å, 1360.18 ± 0.15 Å and 1366.42 ± 0.15 Å and occur in the spectrum of $\beta$ Gru and also the solar spectrum (Jordan et al. 1978a).

A broad feature, or perhaps the combination of a broad and narrow feature occurs around 1309-1310 Å. Its possible origin in terms of Si II (uv 3) or S I ($3p^4\ {}^1D_2 - 3p^3\ 3s\ {}^1D^o_2$, Tondello, 1972) has been discussed by Brown et al. (1984) and Jordan and Judge (1984). The feature appears in stars as early as $\beta$ Dra (G2 II) and as late as $\beta$ Gru (M3 II) and is relatively stronger in the bright giants and supergiants than the giants. It is present only where there are other indications of a high opacity - eg through strong lines of O I (1641.3 Å) and C I (1993.6 Å). Given its proximity to O I and the way it reflects the O I line profile it <u>could</u> be a broad level, such as that in S I, above the first ionization limit, populated by photo-excitation by O I. The photoionization edge of S I from the $^1D_2$ level lies nearby. However, the whole feature could be understood in terms of excitation of Si II (1304.37 Å) by O I (1304.86 Å), the resulting profile of Si II (1309.27 Å) reflecting the asymmetry of the pumping process.

Given the presence of molecules in the photospheric spectra of cool stars it is at first sight surprising that there is not clear evidence of molecular fluorescence in the uv spectra. Fluorescent excitation of $H_2$ and CO by H Ly $\alpha$ and strong transition lines has been identified in the Naval Research Laboratory's spectra of sunspots, obtained with their High Resolution Telescope and Spectrograph (HRTS) (Jordan et al. 1978a, 1978b). Ayres, Moos and Linsky (1981) suggested that CO emission, excited by the O I lines could be present in the spectrum of $\alpha$ Boo (K2 III), at ~ 1340 Å, 1380 Å and 1420 Å; lines also appear at these wavelengths in low resolution spectra of α Tau. A high resolution spectrum of α Boo has been obtained recently to investigate this possible C O emission (Ayres et al. 1984) and weak broad patches of emission do seem to be present at the relevant wavelengths. The one object, other than the sun, from which $H_2$ fluorescence emission pumped by H Ly α has been definitely identified is the pre-main-sequence star T Tauri (Brown et al. 1979). The emission extends away from the star and is excited above the stellar atmosphere in the nearby gas cloud. The most likely explanation for the absence of stronger molecular emission in the cool giants and supergiant spectra is the high opacity between the source of excitation (eg H Ly α and O I) and the lower layers where the molecules exist.

Although space does not permit a full discussion there is evidence that photoionization or photo-excitation to high n states plays an important role in atoms such as S I and C I which have ionization limits near H Ly α. Judge (1984) has found that collisional excitation alone is not sufficient to account for the strength of the S I spectrum. Photo-excitation followed by cascades, radiative and di-electronic recombination also contribute to the observed emission in uv 1 and uv 3. The weakness of uv 5 relative to uv 2 can be caused by a high opacity in uv 5 transferring photons to uv 2 via the 4p $^3P$ term. This should give rise to strong emission at 1.89 μ.

## SPECTROSCOPIC DIAGNOSTICS AT LOW DENSITIES

Having established line identifications in the cool giants and supergiants the subsequent modelling of the atmosphere from absolute line fluxes relies heavily on independent measurements of plasma parameters, particularly the electron density and total gas density. If strong turbulent motions or winds exist modelling from the emission measure using hydrostatic solutions gives only lower limits to the extent of the atmosphere.

Most of the density diagnostic techniques developed for solar work involve lines of at least doubly charged ions. The relative intensity of the intersystem line of C III, $2s^2\ ^1S_o - 2s2p\ ^3P_1$ to permitted lines remains sensitive to $N_e$ down to $N_e \sim 10^9\ cm^{-3}$ and is still useful in the G bright giants. If one could be certain that the atomic data for level populations and ion populations were sufficiently accurate then the ratio of the Si III]/C III] lines at 1892 Å and 1909 Å provides a means of measuring departures from solar abundance ratios in evolved giants and supergiants. At the very low densities ($N_e \lesssim 10^6\ cm^{-3}$) in planetary nebulae the ratio of the magnetic quadrupole transition $2s^2\ ^1S_o$-$2s2p\ ^3P_2$ to that of the corresponding $^1S_o$-$^3P_1$ transition becomes density sensitive and the relevant atomic data are available (Nussbaumer and Schild, 1979, Keenan et al. 1984). This ratio places useful constraints on wind solutions for cool star atmospheres. The most sensitive and useful method to date for measuring $N_e$ in low gravity stars cooler than ~ K 0 involves the C II] multiplet at ~ 2325 Å. Because of the range of A-values three pairs of relative intensities within the multiplet yield values of $N_e$ (for the range $10^7$-$10^9\ cm^{-3}$). The atomic data available (Jackson, 1972; Dankwort and Trefftz, 1978; Nussbaumer and Storey, 1981) do not yield precisely the same values of $N_e$ when applied but the discrepancies are not large (about a factor of two). Calculations of



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the line ratios have shown that $N_e \sim 2 \times 10^8$ cm$^{-3}$ at $T_e \sim 10^4$ K in the K and early M giants and bright giants but $\sim 10^7$ cm$^{-3}$ in the M supergiant α Ori. The total flux in the C II multiplet relative to permitted lines is also density sensitive for $N_e \gtrsim 10^9$ cm$^{-3}$. But at $N_e \lesssim 10^9$ cm$^{-3}$ the C II lines are more useful as a temperature diagnostic. Collision cross-sections for both the C II multiplet and the resonance lines at 1335 Å have recently been calculated by Hayes and Nussbaumer (1984) and their lower cross-section for the resonance lines resolves an anomaly in the apparent electron temperature derived from the 2325/1325 Å line ratio in α Tau and β Gru (Brown, Ferraz and Jordan, 1981).

At $T_e \lesssim 10^4$ K a measurement of the electron density does not also determine the total gas density since important species, eg hydrogen and helium, are not fully ionized. Opacity sensitive line ratios provide a valuable way of measuring the value of $\int N_H \, dh$ in the following way. The ideal case is where a strong resonance multiplet shares a common upper level with a semi-forbidden transition of substantially lower transition probability. Then, whilst the resonance lines become optically thick, the semi-forbidden line does not. A measurement of the line ratio, under assumptions concerning line profiles, allows the probability of escape and opacity in the resonance lines to be found, and hence $\int N_H \, dh$. Since the mean emission measure gives $\int N_e N_H \, dh$ an independent rough estimate of $N_e$ can also be found. The lines of C I (1656 Å and 1994 Å) (Jordan, 1967) and O I (1302, 1305, 1306 Å and 1641 Å) (Brown, Ferraz and Jordan, 1981) are examples of this method. Although the branching ratios for C I have recently been measured and re-calculated (Tossi, Huber and Pauls, 1984) the transition probability used for the O I line at 1641.31 Å (Garstang, 1961; Müller, 1968) has not been re-examined in recent years.

## DIRECTIONS FOR FUTURE WORK

Much of the high resolution spectroscopy of cool stars is now being carried out with exposures of up to ~ 22 hours. However it is still not possible to detect some of the unidentified emission seen at low resolution. Since the wavelength regions of interest have been established the Space Telescope high resolution spectrograph will be an ideal instrument for further work on cool stars. Similarly one could hope to improve and extend the observation of the density sensitive C II ratios which are not ideally placed regarding the sensitivity of the IUE long wavelength cameras.

Although neutral atoms are now well studied in laboratory sources and the situation for the singly charged metals has improved in recent years there is still a need for investigations of high levels near and above the first ionization limit.

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