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The chemical composition of Algol systems – I. The secondary in U Cephei

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Summary. 1.9 Å resolution Reticon spectra of the secondary component of the close binary system U Cep (B7 V + G8 III) have been obtained. The spectra were centred at 6320 and 8620 Å and are 430 Å wide. From a differential spectrum synthesis relative to κ Gem the metal abundance in the secondary component of U Cep is found to be normal, [Fe/H] = 0.0 ± 0.3. The abundance of *s*-process elements also appears to be quite normal. Since the U Cep system is a result of case A mass exchange the observed abundances in the secondary component are consistent with that expected from theory.

The Ca II infrared triplet lines are found to be very weak in the spectrum of the secondary components of U Cep and U Sge. Weak Ca II IR triplet lines are also noticed in σ Gem, a single lined spectroscopic binary with strong K-line emission. Enhanced chromospheric emission in the H and K lines seems to be accompanied by a weakening of the infrared absorption lines of Ca II. The secondary components in U Cep and U Sge appear to have active chromospheres as a result of tidal effects.

1 Introduction

In Algol type close binary systems, the more massive primary is an early-type main sequence star and the less massive secondary is evolved and is typically a subgiant or giant of late spectral type. The system has resulted from a large-scale transfer of mass as the secondary which was the more massive star in the original binary, evolved, filled its Roche lobe and lost mass to the primary (Crawford 1955; Kopal 1955). Clearly, a detailed analysis of the chemical composition of the primary and secondary components could shed light on the mass transfer event.

Information on the secondary components has been obtained primarily from radial velocity and photometric studies. Broad-band photometry has indicated a large ultraviolet excess for the secondaries (Koch 1972). Miner (1966) utilized narrow-band photometry to study 12 Algol secondaries. The spectral features measured by him were the G-band, the

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CN bands at 4200 Å and a metallic abundance index m'. He found a metal deficiency for all 12. From the correlation of the $\Delta m'$ index (Miner 1966) with [Fe/H], Hall (1967) (also see Koch 1972) found the average [Fe/H] for the 12 secondaries to be −0.96. McNamara (1967) and McNamara & Feltz (1976) from *uvby* photometry found [Fe/H] = −0.9 and −0.6 for the secondary components of U Cep and U Sge respectively. Similar metal deficiencies were reported by Hall (1967) who measured the CN index defined by Griffin & Redman (1960).

Only recently has an abundance analysis for the secondaries been attempted from high dispersion spectra. Naftilan (1976) used spectrum synthesis and curve of growth approaches to analyse the spectrum of the secondary of U Sge. Spectra in the interval 3500 to 4800 Å led to a mild metal deficiency ([Fe/H] ~ −0.7) for the iron group and similar elements, but a slight enhancement was found for some *s*-process elements. This is an intriguing result which, if confirmed and extended to other Algol systems, surely places severe constraints on the mass transfer models.

In this series of papers we propose to report the results of new spectroscopic analyses of the primary and secondary components of Algol systems. Several factors suggest that the investigation will yield useful results. The spectra show severe rotational broadening so that normally strong lines are broad and shallow. Accurate definition of weak line profiles is now possible with modern digital detectors. The line blending and continuum level uncertainty associated with the crowded spectra of G and K stars are both exacerbated by the rotational line broadening. These difficulties are minimized by working with the much less crowded red and near-infrared spectra. Again, this is possible with modern digital detectors. Uncontaminated spectra of the secondary can be obtained only in the total phase of the primary eclipse. Since the duration of totality is short and the secondary is faint, the acquisition of spectra of the necessary high quality is a challenge to high quantum efficiency detectors. U Cep and U Sge, which at minimum light have $V \sim 9.1$ and 9.2 respectively, are the two brightest Algol systems with total primary eclipses.

In this paper, we present an abundance analysis of the secondary of the U Cep system and show that it has a normal metal abundance within a moderate uncertainty.

2 Observations

Our spectra of U Cep were obtained near the middle of primary eclipse using the McDonald Observatory 2.7-m telescope and the Tull coudé spectrometer equipped with a Reticon silicon diode array detector (Vogt, Tull & Kelton 1978). Single exposures covering 430 Å were obtained at a resolution of 1.9 Å with 0.46 Å per diode. With an exposure time of about 50 min in average seeing the unsmoothed spectra have a signal/noise ratio of about 80. Each exposure was centred near mid-eclipse and had a duration much shorter than the duration of totality so that the secondary spectrum was obtained without contamination from the primary. The spectra were centred at 6200 and 6320 Å. These regions were selected because examination of the Arcturus spectrum (Griffin 1968) suggested that they contained a useful mixture of moderately strong lines and broad continuum regions. An additional spectrum, which was centred at 8620 Å and included the Ca II infrared triplet lines at 8498, 8542 and 8662 Å, was observed. The UT times of mid-exposure were $02^h\,33^m$ 1977 December 2 (6200 Å), $07^h\,47^m$ 1978 February 22 (6320 Å) and $10^h\,35^m$ 1977 July 25 (8620 Å). The resolution of 1.9 Å was chosen to match the anticipated rotational broadening.

Spectra were also obtained of several standard stars: δ CrB (G5 III), κ Gem (G8 III) and β Gem (K0 III) and γ Cep (K1 IV). The lines in the spectra of the standard stars, which were observed at the same resolution, are sharper than in U Cep (see Fig. 1). This demon-

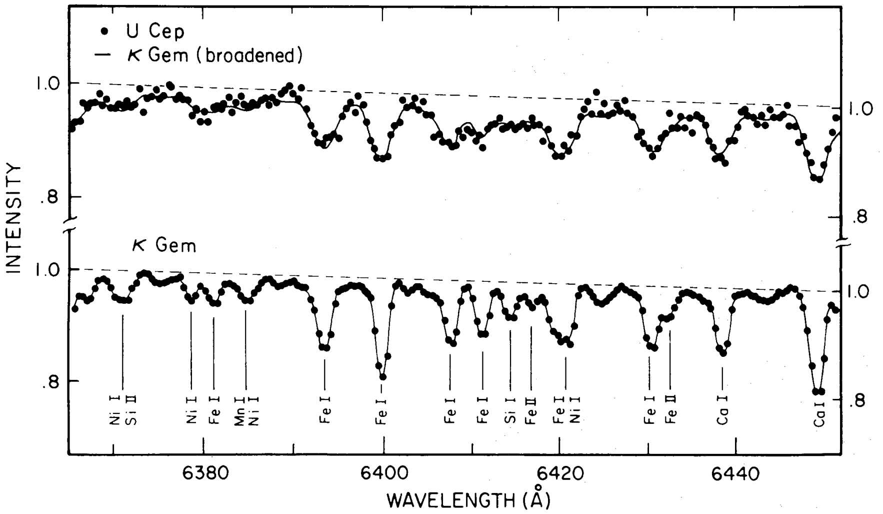

Figure 1. Spectra of κ Gem and the secondary component of U Cep.

strates that the resolution is sufficiently high that the broadening of the U Cep spectra is mostly rotational, not instrumental. The envelopes defined by the high points in the U Cep spectra matched the envelopes of the corresponding standard star spectra. Thus we were able to define the continuum accurately over the length of each U Cep spectrum.

3 Analysis

3.1 THE ROTATIONAL VELOCITY OF THE SECONDARY

In the spectrum synthesis approach to an abundance analysis, the line broadening resulting from the rotation of the secondary must be taken into account. The orbital period and stellar radius of 4.7 $R_\odot$ (Batten 1974) correspond to a predicted equatorial rotational velocity of 95 ± 10 km s^{-1} on the assumption that the secondary is rotating synchronously. To check this prediction, we matched the U Cep secondary spectra to Gaussian broadened spectra of the standard stars. The broadening velocity, V_G, of the Gaussian velocity distribution, $\exp[-(V/V_\mathrm{G})^2]$, is related to the rotational velocity by $V_\mathrm{G} = 2/3\ V_\mathrm{Rot} \sin i$ (Unsöld & Struve 1949). A rotational velocity of 90 ± 8 km s^{-1} ($V_\mathrm{G} = 60$ km s^{-1}) applied to the κ Gem spectrum provides an excellent fit to the U Cep secondary spectrum (Fig. 1). The spectral type of κ Gem is G8 III (Batten 1974) and matches the classification of the secondary of U Cep. The rotational velocity solution is not sensitive to the choice of standard star. The result shows that the secondary is rotating synchronously.

3.2 THE CHEMICAL COMPOSITION OF THE SECONDARY

Since the spectrum of the secondary is so severely broadened by rotation, a spectrum synthesis approach is especially attractive. Our analysis was done in two stages.

The standard star κ Gem is a close match to the U Cep secondary. For κ Gem, Williams (1971) obtained the basic parameters $T_\mathrm{eff} = 4990$ K and $\log g = 2.9$. The composition of κ Gem appears to be solar (Burbidge & Burbidge 1957; Williams 1971; Hansen & Kjaergaard 1971).

Colour indices and the spectral type suggest $T_\mathrm{eff} = 5000$ K for the U Cep secondary (Batten 1974). Cester *et al.* (1977) from light curve synthesis obtained $T_\mathrm{eff} = 5080$ K. The known mass and radius (Batten 1974) provide $\log g = 3.5 \pm 0.2$.

Since the neutral metal lines are relatively insensitive to small differences in the surface gravity our initial analysis took the observed κ Gem spectrum and broadened it by the predicted amount for synchronous rotation. The fit to the observed U Cep secondary spectrum was excellent (Fig. 1). Clearly, large abundance differences between U Cep and κ Gem are excluded by this direct test.

In order to obtain a quantitative understanding of the abundance similarity, we undertook to account for the difference in gravity between κ Gem and the U Cep secondary. A model atmosphere with $T_{\text{eff}} = 5000$ K, $\log g = 3.0$ and solar composition was taken from the grid constructed by Bell *et al.* (1976). We synthesized two spectrum intervals: 6139.0 to 6158.5 Å and 6377 to 6409 Å. An initial line selection was made using the Kurucz & Peytreman (1975) table. A total microturbulent velocity of 2 km s^{-1} was adopted with a macroturbulence of 4 km s^{-1}. The computed spectrum was convolved with the instrumental profile. Through adjustment of the oscillator strengths, the synthetic spectrum was forced to match the observed spectrum of κ Gem. In the next step, we retained the revised oscillator strengths and recomputed the spectrum for model atmospheres $T_{\text{eff}} = 5250$ K, $\log g = 3.75$; $T_{\text{eff}} = 5250$ K, $\log g = 3.0$; $T_{\text{eff}} = 5000$ K, $\log g = 3.0$ (the κ Gem model), and three different input abundances, solar, one-third solar and one-tenth solar. To match the U Cep spectra, the synthetic spectra were rotationally broadened. The calculations with three different models enable us to assess the effect of reasonable temperature and surface gravity uncertainties on the synthetic spectra. Observed and synthetic spectra in the wavelength interval 6377 to 6409 Å are compared in Fig. 2. The spectrum computed for solar abundances for model atmosphere $T_{\text{eff}} = 5000$, $\log g = 3.0$ is a good fit. It is clear that with the other two models the solar abundance synthetic spectra also provide the best fit.

Since the rotational broadening is so severe, the shallow lines in the U Cep secondary spectrum correspond to deep saturated lines in the κ Gem spectrum. Hence, their conversion to a metal abundance is subject to modest uncertainty. Inspection of the synthetic spectra suggests that [Fe/H] = 0.0 ± 0.3 where the uncertainty includes a contribution from the

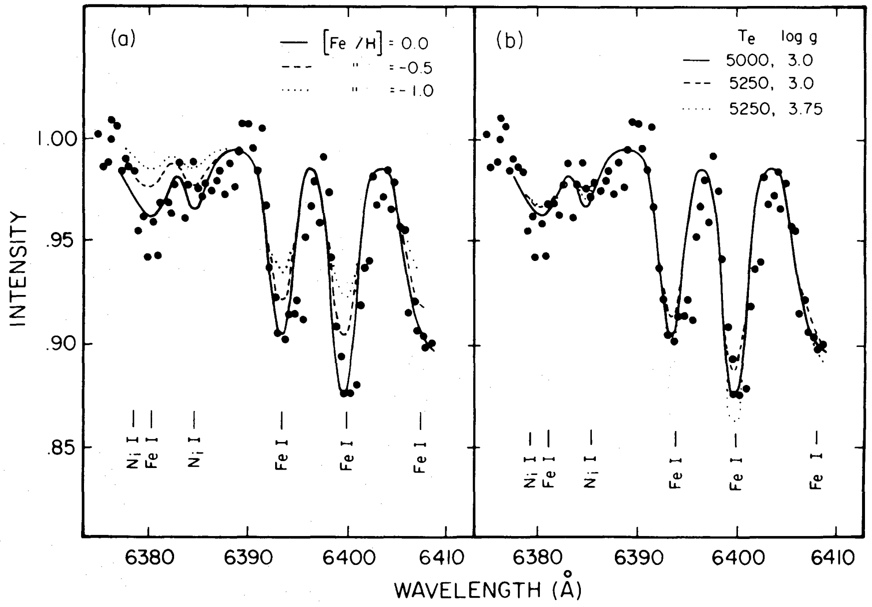

Figure 2. The spectrum of the secondary component of U Cep between 6380 and 6410 Å. The synthetic spectra in (a) show the effect of a decrease in the adopted metal abundance; a model atmosphere T_e = 5000 K and $\log g = 3.0$ was adopted. Synthetic spectra in (b) show the sensitivity of the synthetic spectra to changes in the adopted effective temperature (T_e) and surface gravity ($\log g$); they were computed with solar metal abundances.

$T_{\rm eff}$ and $\log g$ uncertainties. Our results are in agreement with Baldwin (1973) who, from a spectral comparison of the secondary of U Cep with single stars of the same spectral type, also found no evidence of significant metal deficiency. They exclude the metal deficiency, [Fe/H] = -0.9 (McNamara 1967), obtained from narrow-band photometry.

The majority of the lines belong to metals in the range Na to the iron group. The Ba II line at 6141.7 Å is included and appears to correspond to a solar abundance. Therefore, we suggest that the *s*-process elements also have a solar abundance. This contrasts with Naftilan's (1976) results for the U Sge secondary where he reported a metal deficiency but an *s*-process overabundance. From a comparison of the broadened spectrum of δ CrB (G5 III) with the spectrum of the secondary of U Sge in the wavelength interval 8400 to 8800 Å, we exclude the possibility of significant metal deficiency. Clearly, it would be of great interest to extend our analysis to U Sge and other Algol systems in order to define the range of abundance anomalies which may be related to processing in the star.

Our analysis of the U Cep secondary spectrum is clear evidence for normal abundances of iron peak elements. We therefore conclude that the interpretation of the UV excess obtained from the broad-band and narrow-band photometry as as indicator of metal abundance is invalid. The cause of the UV excess could be due to circumstellar gas.

Rhombs & Fix (1976, 1977) made flux measurements of U Cep during totality and also outside the eclipse covering the wavelength interval 3300 to 5900 Å with a bandpass of 30 Å. They found that a large UV excess seen during totality in 1974 was absent in 1975. Similar results were reported by Batten *et al.* (1975) and Olson (1976). If a similar UV excess affected the photometric observations of the secondary of U Cep it would provide an explanation of the discrepant photometric metal abundances. The Rhombs & Fix measurements of the secondary of U Cep show the excess UV flux increases steeply shortward of 4000 Å. There is no significant excess flux at longer wavelengths. Excess flux with this distribution will affect the u band (central wavelength 3500 Å) but not the v, b and y bands (central wavelengths 4110, 4670 and 5470 Å, respectively). The [Fe/H] of -0.9, estimated by McNamara (1967) for the secondary of U Cep, is based on the difference between its m_1 index (which is independent of u) and the m_1 indices of stars in the same location of a c_1 versus $b-y$ diagram. The c_1 index depends directly on u and therefore may provide a misleading location in the c_1 versus $b-y$ diagram and, hence, a misleading estimate of the metal abundance. We note, however, that the observations of Rhombs & Fix were made during the 'outburst-mass transfer activity', a rare event described by Batten *et al.* (1975) and Plavec & Polidan (1975). If the photometry was done during a quiescent phase, when the UV excess was greatly reduced, then an alternative explanation of the discrepancy between the photometric and spectroscopic abundances must be sought.

Finally we note that the Ca II infrared triplet lines (see Fig. 3) are weak in the secondary of U Cep (and also in U Sge) relative to standard stars. In comparing the spectra, the standard star spectra are broadened by the predicted rotational velocities. More observations are needed to confirm our suspicion that the Ca II lines are weaker in all Algol secondaries.

In normal stars the cores of the Ca II lines (and the H and K lines) are formed in the chromosphere. H and K line emission intensity is found to be an indicator of chromospheric activity (Wilson & Bappu 1957; Wilson 1963). Since the H and K lines and the infrared triplet share a common upper state, enhanced chromospheric emission in the H and K lines is likely to be accompanied by a weakening of the infrared absorption lines. Baldwin (1973) reported that the Ca II K line in the spectrum of the secondary of U Cep appears to be filled in by emission.

The correlation between strong H and K emission and weaker absorption lines of the Ca II infrared triplet may well be present in other binaries with a late-type giant component.

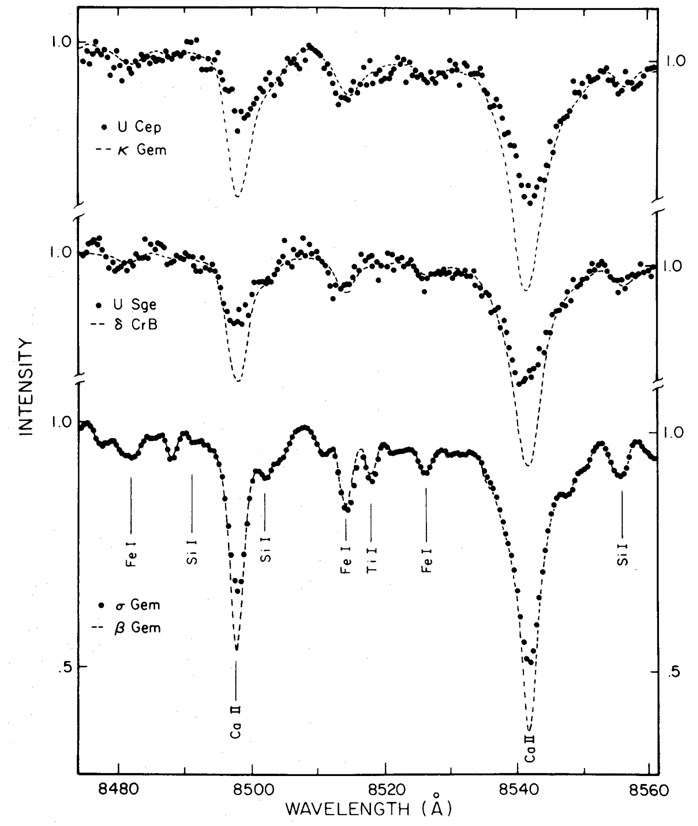

Figure 3. The infrared Ca II lines at 8498 and 8542 Å. Spectra of the secondaries of the U Cep and U Sge systems are compared with the spectra of appropriate standard stars. The latter spectra are shown after convolution with the rotational broadening function which is appropriate for the synchronously rotating secondary.

An example is σ Gem (K1 III, *P* = 19.6 day) which is a single lined spectroscopic binary with K-line emission intensity of 5 on the scale of Wilson & Bappu (1957) and Wilson (1976). Our infrared spectrum of σ Gem shows that the triplet lines are weaker than in a standard star of similar spectral type (Fig. 3). Attribution of the Ca II effects to an enhanced chromospheric activity is confirmed by the detection of a strong He I 10830 Å line in σ Gem (Zirin 1976).

4 Conclusions

Since U Cep is a result of case A mass exchange (Paczynski 1971) the observed normal abundances of metals [Fe/H] = 0.0 ± 0.3, and *s*-process elements in the secondary component are consistent with that expected from the theories of evolution of close binary systems. This contrasts with Naftilan's (1976) results for the secondary component of U Sge. However the two systems may be the result of two different cases of mass exchange. The observed mass ratios are $q = 0.67$ for U Cep (Batten 1974) and 0.33 for U Sge (Cester *et al.* 1977). U Sge may be an old Algol system and probably the result of case B mass exchange (Plavec 1973). The mass ratio of the U Cep system is higher compared to other Algol systems and recent observational evidence for large-scale mass-transfer activity (Batten *et al.* 1975; Plavec & Polidan 1975) indicates that the system may be relatively younger. Detailed analysis of the chemical composition of the primary and secondary components in close binary systems in different stages of evolution and which have undergone different cases of mass transfer is needed.

Further observations of the Ca II K and IR triplet lines in the secondary components of Algol systems and other late-type spectroscopic binaries will enable us to understand the causes for the enhanced chromospheric activity in these systems.

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Note added in proof

The photometric index that Miner (1966) used as an indicator of metal abundance measured the strength of the G band at 4300 Å. The weakness of this index in the 12 Algol secondaries observed by Miner may indicate that CH, which is a major contributor to the G band, is weak in secondaries. This would suggest an underabundance of *carbon* not, as has been generally supposed, an overall underabundance of metals. Such a carbon underabundance would be consistent with the effect of CNO processing that, as a result of mass loss, the secondaries are expected to evidence.