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OAO observations of magnesium II emission in late-type stars

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The presence of Ca II H and K emission and $\lambda = 1083$ nm of He I in late-type stars suggests that the outer atmospheres of these stars bear some resemblance to the solar atmosphere. Dr Zirin has discussed the appearance of these features in a number of stars in the preceding paper. Because spectral features in cool stars are most sensitive to temperature differences in the ultraviolet, observations of ultraviolet spectra should yield considerable information concerning the nature of chromospheric structure in stars. Over the past year the Orbiting Astronomical Observatory OAO-2 has scanned a number of bright stars of spectral type G and later in the region 180 to 370 nm with a resolution of about 2.5 nm. I will discuss some of the characteristics of these low-resolution spectra with particular emphasis on the appearance of the $\lambda = 280$ nm doublet of Mg II.

Code *et al.* (1970) have described the OAO instrumentation and its operation. The spectra were recorded with an objective-grating spectrometer employing an EMI 6256 B photomultiplier and a collecting area of 265 cm^2. The data consist of digital counts integrated 8 s at each 2 nm step of the grating. A pre-counter stores one count in the spacecraft memory for every 64 photomultiplier events. Thus the limiting accuracy even at low counting levels is set principally by the pre-counter truncation rather than by photon noise. The response of the spectrometer is fairly flat between 360 and 220 nm. A preliminary calibration of the absolute response near 280 nm, based on scans of G 2 V and GO IV stars and the solar flux (Brinkmann, Green & Barth 1966) yields 4.6 aJ $cm^{-2}\,s^{-1}$ per OAO (reduced) count. Figure 1 shows the excellent agreement between the spectral features of α Cen and the Sun seen with a slightly better resolution of 2 nm. Here the solar spectrum has been normalized to α Cen at 290 nm. The gradual decrease of the flux of α Cen relative to the Sun is real and consistent with the somewhat redder colour of α Cen (B–V = 0.68). Mg II appears as a deep, single absorption feature. Mg I $\lambda = 285.2$ nm is also strong.

Comparison of the long-wavelength portions of the scans with ground-based photometry indicates an increasing contribution of scattered light with later spectral type. For M stars this may amount to 50 % of the light near 350 nm. How the scattered light varies with wavelength has not yet been determined. The Earth's radiation belt also affects the level of some scans. For these reasons I will not attempt to present spectral energy distributions.

Table 1 lists the stars observed, their V magnitudes and spectral types. Selected scans of three of the brightest stars are shown in figure 2. α Boo and α Tau are single scans, while α Ori is the mean of six scans. These spectra appear to be free of background variability due to the radiation belt. The dashed lines are approximate black-body fluxes for the temperature (θ) indicated. These fluxes are based on the V magnitudes of the stars, the scales of effective temperature and bolometric correction given by Johnson (1966), and a constant instrumental response equal to the response at 280 nm. Shortward of 285 nm the only identifiable feature in the spectrum of α Boo is strong Mg II emission. In this region the radiation temperature of the continuum is less

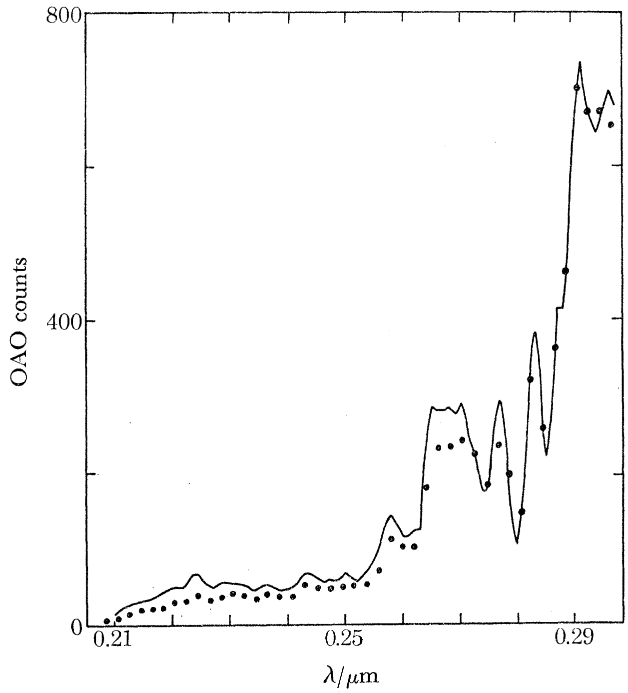

FIGURE 1. Comparison of a scan of α Cen (...) with the Sun (—). The solar energy distribution at 2 nm resolution has been folded into the spectrometer response curve and normalized to α Cen at $\lambda = 0.29\ \mu m$.

TABLE 1

star	type	*V*	Mg II counts max.	Mg II counts min.	Mg II counts best	*IW*
β And	M0 III	2.03	4	3	3	0.56
λ And	G8 III–IV	3.88	2	—	—	0.57
γ Aql	K3 II	2.62	2	—	—	0.30
α Ari	K2 III	2.00	2	—	—	0.48
α Aur	G5 III + G0 III	0.09	25	—	—	< 25
ι Aur	K3 II	2.66	2	—	—	0.30
α Boo	K2 IIIp	0.06	12	7	9	2.96
η Boo	G0 IV	2.69	2	—	—	< 0.31
α Cas	K0 II–III	2.24	2	—	—	< 2.2
α Cen	G2 V + K	−0.3	30	—	—	—
θ Cen	K0 III–IV	2.05	1	—	—	< 2.8
ζ Cep	K1 Ib	3.36	2	—	—	0.24
η Cep	K0 IV	3.43	1	—	—	0.12
ι Cep	K1 III	3.55	1	—	—	< 0.70
β Dra	G2 III	2.87	4	—	—	1.32
δ Dra	G9 III	3.10	1	—	—	< 1.1
η Dra	G8 III	2.77	1	—	—	0.36
γ Eri	M0 III	2.96	2	—	—	< 0.41
β Her	G8 III	2.83	1	—	—	0.28
ζ Her	G0 IV	2.82	1	—	—	< 0.26
β Hyi	G2 IV	2.79	1	—	—	< 1.5
γ Hyi	M2 II–III	3.24	1	—	—	< 0.29
α Ori	M2 Iab	0.80	9	6	7	2.23
β Peg	M2 II–III	2.56	2	—	—	0.46
α Sco	M1 Ib	1.08	—	5	7	1.85
α Tau	K5 III	0.86	10	5	8	1.29
α UMa	K0 II–III	1.79	2	—	—	0.84
β UMi	K4 III	2.08	1	—	—	0.44

than about 3100 K. Mg II emission is also strong in α Tau and α Ori. There is no clear evidence of other spectral features in these stars shortward of about 310 nm. Variations in spacecraft pointing equivalent to one grating step can occur, and this accounts for the greater width of Mg II in α Tau. The maximum radiation temperature of the continuum in α Tau is lower than in α Boo and still lower in α Ori, as expected from their effective temperatures. However, there are differences between these scans that set α Tau and α Ori apart from α Boo and the other stars observed.

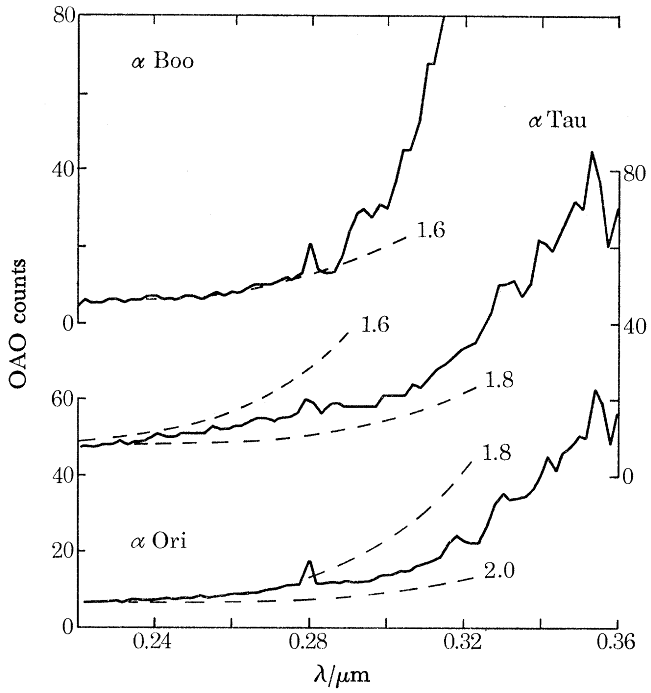

FIGURE 2. Selected scans of three bright stars. The dashed lines are black-body fluxes without correction for instrumental response or variable background (see text).

In general, the shorter the wavelength the more rapidly the flux decreases with advancing spectral type. This trend reverses with α Tau where, although the ratio of the flux at 290 nm to the flux at 350 nm is about the same as in α Boo, the flux shortward of the Mg II lines is nearly as great as at 290 nm. In contrast to stars of earlier type, the radiation temperature in α Tau appears to increase with shorter wavelength from a minimum near 300 nm. That scattered light produces this effect seems unlikely. If we suppose that the apparent continuum in α Boo shortward of 285 nm is entirely scattered light, then scattered light cannot account for more than about half the apparent continuum of α Tau in this region. α Ori also appears to have a temperature minimum near 300 nm. Whether the occurrence of a minimum indicates a transition from a Fraunhofer to an emission-line spectrum cannot yet be determined from the scans. The minimum may reflect a decrease in the 'unknown opacity' with lower temperature as Bonnet (1968) finds for the Sun.

It has been known for some years that Fe II emission is present in α Ori. These lines belong to multiplets (1), (6) and (7) with wavelengths near 320 nm. Weymann (1962) classifies these lines into three groups according to their intensity and appearance. Lines of group (*a*) are the strongest and show central reversal. Weymann estimates that $\lambda = 327.7$ nm, one of the (*a*) lines, has a peak intensity about twice the background and a width of 80 pm. If we suppose, allowing for scattered light, that the flux in α Ori is 10 counts and that this corresponds to half of Weymann's background then $\lambda = 327.7$ nm contributes 1 count. If the six remaining (*a*) lines between $\lambda = 318.5$ and $\lambda = 322.7$ nm have the same intensity, it is reasonable to suppose that Fe II emission produces all of the observed peak at $\lambda = 318$ nm in figure 2. Whether these lines are formed in analogy with solar Ca II and Mg II is not known. One possible mechanism is ruled out by the OAO observations, however. If the near-ultraviolet lines originated in an optically thin envelope, then their upper levels should produce observable emission in the three ultraviolet multiplets (u.v. 1), (u.v. 62), and (u.v. 63). On the assumption that every group (*a*) line has one count of emission and with relative transition probabilities taken from Corliss & Bozman (1962) and Warner (1967), we should expect 10^3 counts distributed over the region 258.5 to 277 nm. There is no difficulty explaining the absence of these lines if high opacity limits their intensity to the same brightness temperature as $\lambda = 327.7$ nm, which appears to be around 2800 K. At this temperature, and with the same width as $\lambda = 327.7$ nm, the total effect of the ultraviolet Fe II lines amounts to only 3 counts.

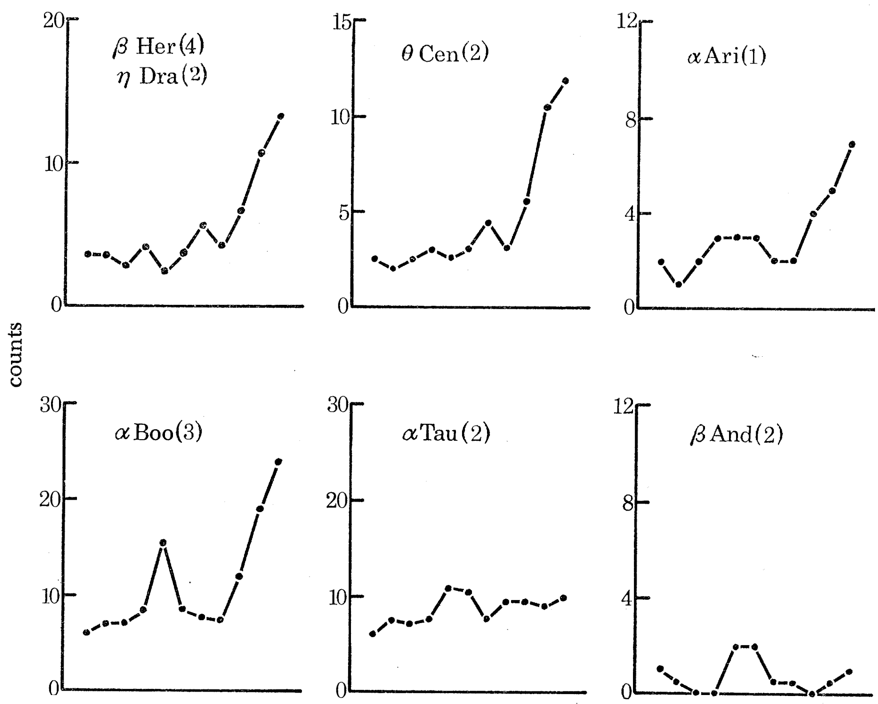

FIGURE 3. Averaged scans of the $\lambda = 280$ nm region in giants with sky background removed. The number of scans averaged is given in parentheses.

Figures 3 and 4 illustrate the Mg II region for selected stars. Where possible, scans have been averaged to reduce noise. Since wavelength registration may vary from star to star, no wavelengths are indicated in the figures. The segments are arranged so that $\lambda = 280$ nm falls between the fifth and sixth channels. Sky background has been subtracted. From figure 3 we see that normal G 8 giants closely resemble the Sun. With later spectral type, Mg II rapidly becomes an emission feature. There is some indication that Mg I $\lambda = 285.2$ nm also goes into emission. Channels 6 to 8 are identical in the two scans of α Tau, and channel 8 must be centred on the Mg I line. Among the supergiants (figure 4) only α Sco and α Ori definitely show Mg II emission. The single scan of α Sco has a high and uncertain background due to the radiation belt, and the zero point is chosen to agree with α Ori.

In summary, it appears from the limited data available that the transition from Mg II absorption to emission at 2.5 nm resolution occurs at K 2 for both giants and supergiants.

The circumstances of formation of the emission in the H and K lines of Ca II and Mg II must be quite similar, as the discussion of the solar case by Athay & Skumanich shows (1968*a*). Using generalized chromospheric models Athay & Skumanich (1968*b*) have investigated the dependence of the principal features of stellar Ca II emission on temperature gradient, density and velocity fields. There is no similar treatment of Mg II, but the different abundances of these ions and consequently different optical depths of formation suggest the likelihood of wide variation in the ratio of Ca to Mg strength in stars, where the outer atmosphere may be very different from the Sun's. Thus it is interesting to compare Mg II and Ca II for the stars observed here.

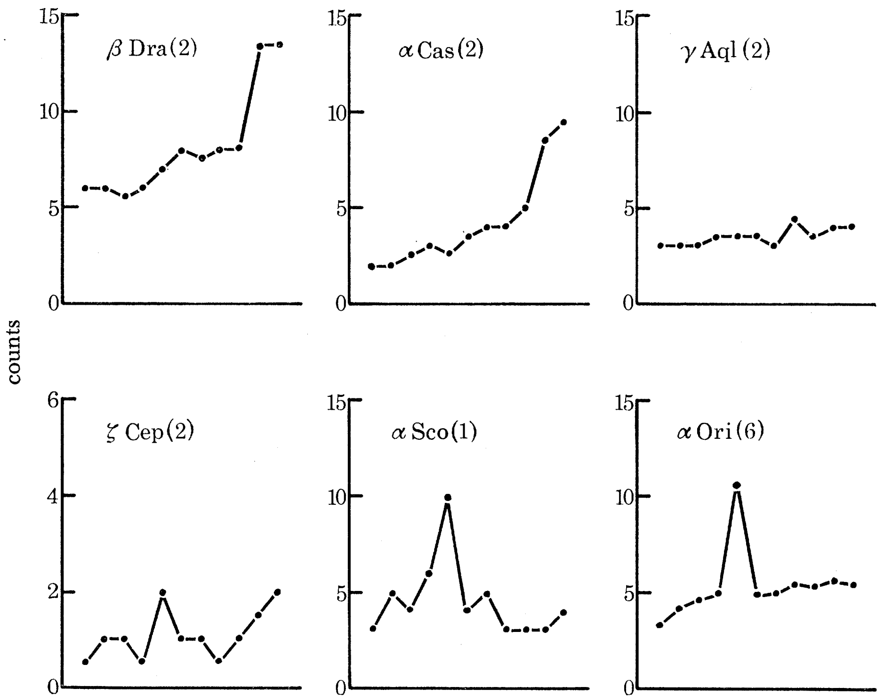

FIGURE 4. Averaged scans of the λ = 280 nm region in supergiants, as in figure 3. The zero point for α Sco is arbitrary.

Observed Ca II fluxes have been described in terms of the local continuum (Wilson & Bappu 1957; Liller 1968; Wilson 1970). This is not possible with the present Mg II data. Nor is there an accepted definition of the total flux 'in emission' for lines of this type. I will suppose that the Mg II data at least set limits to the total flux in the H and K emission cores and compare these values with estimates of the total flux in the Ca II K emission core. In table 1, column 4 gives the maximum Mg II flux as the difference between the number of counts above sky background and one-half the apparent continuum for the spectrometer slit centred on the Mg II lines. This assumes that the underlying absorption feature has at most the same equivalent width as in the Sun. For stars with clear emission, column 5 gives the minimum flux as the number of counts above the apparent continuum. For these stars I also list in column 6 a 'best' value, which is calculated similarly to column 4 but with my estimate of the true continuum rather than the apparent continuum. Finally, column 7 gives the total flux in the emission core of Ca II K computed as follows: Liller (1968) determined peak emission intensities I' relative to two side bands centred at 387.8 and 398.8 nm. As a relative measure of the flux in these bands take the quantity F defined by

$$m = -2.5 \lg F,$$

where m is the apparent magnitude of the star in the 400 nm narrow-band filter of Johnson, Mitchell & Latham (1967). The peak flux is then $I = I'F$ and the total emission flux IW, where W is the width of the emission core ($km\,s^{-1}$) given by Wilson & Bappu (1957). Liller's (1968) calibration of their eye estimates of intensity extends the calculation of IW to most of the stars in table 1. For the remaining stars I have assumed an upper limit of $I' = 1$ and an average W for the luminosity class.

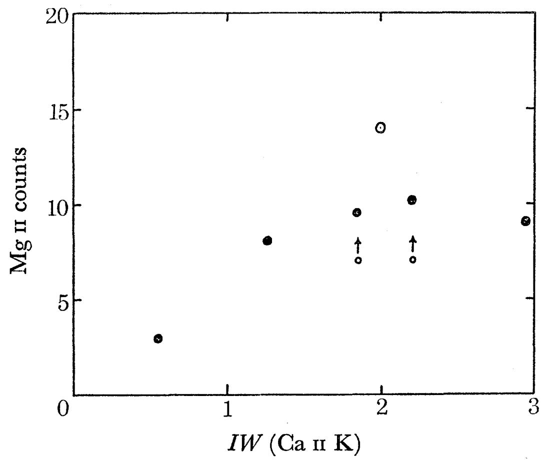

FIGURE 5. Mg II emission flux versus Ca II K flux for five stars (●) and the Sun (☉). The open circles are α Sco and α Ori before reddening corrections. The arrows point to the corresponding filled circles. See text for coordinate definitions.

Figure 5 plots the 'best' Mg II counts against IW. α Ori and α Sco have been corrected for differential reddening according to the intrinsic colours of Johnson (1966) and the reddening curve of Bless, Code & Houck (1968). A straight line

$$\text{Mg II} \cong 4IW$$

represents the observations very well. The remaining stars in table 1 with known Ca II intensities are at least consistent with this relation. Liller (1968) found irregular intensity variations in Ca II up to 20 % in α Boo and α Tau during 5 months of observation. Except for the flare in α Tau, variations over intervals of hours were small. There is no indication of Mg II variability in the OAO scans. For most stars, two scans were made in the same or successive orbits. The six scans of α Ori covered 6 days. Only for α Boo are there suitable scans months apart. Figure 5 includes the Sun as it would appear with $V = 0$. Here the strength of the Mg II emission cores has been estimated from the observed profiles given by Athay & Skumanich (1968*a*) for moderate solar activity. According to Smith (1960), the intensity of the quiet Ca II peak is 0.054 of the continuum at the centre of the disk. Inspection of the Utrecht Atlas in the region of Liller's side-bands and correction for limb darkening leads to $I' = 0.135$, and with $W = 35\,km\,s^{-1}$, $IW = 2$. At solar maximum, IW might increase 40 % (Sheeley 1967). It is remarkable that stars so divergent in effective temperature and gravity exhibit the same line ratio within a factor of two.

Since the method used to calculate IW ignores the K 3 reversal, it is clear that IW and the Mg II counts do not strictly measure the same properties of these lines. This is particularly serious for the Sun, where almost any other method of defining a net emission flux would lead to a much smaller value of *IW*. However, there is another interpretation of figure 5 that may have better physical significance and also justify the use of *IW* for the Sun. For solar Mg II, the H and K profiles are such that dividing the total intensity of either line by the width at half intensity gives the peak intensity to about 10 %. If this is true for stellar Mg II, and if the ratios of the widths of Mg II to Ca II K are the same in the Sun and stars, then the ratio of peak Mg II flux to peak Ca II K flux is the same.

In the context of the analysis of Athay & Skumanich (1968*a*, *b*), peak intensity is a strong function only of chromospheric temperature and electron density. This is true also for the product of intensity and width. It is indeed surprising if the temperature and electron density over a large range of optical depth conspire to produce the same line ratio in all stars when T and N_e must also satisfy the ionization equations and the condition of mechanical equilibrium. Although equally surprising, the alternative conclusion also deserves consideration. That is, the region of the atmosphere that forms Ca II and Mg II emission may be quite similar in all late-type stars.

B. D. Savage first called my attention to Mg II emission in early OAO scans. Discussions with him and with A. D. Code have been most helpful. This research was supported in part by NASA Contract no. NAS 5-1348.

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