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Mass loss from the A-type supergiant α Cygni

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The Mg II resonance lines in α Cygni (A2Ia) are studied from 22 spectral scans obtained by the experiment S59. The cores of the resonance lines are shifted by −130 km/s and the short wavelength side of the core is shifted by about −350 km/s. The lines are compared with predicted profiles in an expanding atmosphere. This comparison suggests a rate of mass loss of $-\mathrm{d}M/\mathrm{d}t \gtrsim 3\times10^{-10}\,\mathscr{M}_{\odot}$/year. The atmosphere seems to be accelerated up to a velocity of 300 km/s. The acceleration might be produced by the near-u.v. resonance lines of singly ionized metals. The observations of the near-u.v. spectrum of A-type supergiants with a high spectral resolution is recommended.

1. The observations

The supergiant star α Cygni, A2Ia, HD 197345, was observed by the Orbiting Stellar Spectrometer S-59 on 25/26 May 1972 and 25/26 May 1973. In total 22 spectral scans of this star were recorded. The averaged spectrum in the wavelength region from 2775 to 2865 Å is shown in figure 1. In the same figure, the spectrum of α Cyg is compared with the spectrum of an average star of type A2, denoted by ⟨A2⟩, which was composed by averaging the spectral scans of β Aur (A2V), α PsA (A3V) and ζ Sgr (A2III).

In general, the lines of α Cyg are deeper than those of the ⟨A2⟩-star. This is probably due to the larger microturbulent velocity in α Cyg. Groth (1961) studied the visual spectrum of this star and found a microturbulent velocity which increases with height from 8 to about 20 km/s.

The Mg II resonance lines at 2795.5 and 2802.7 Å in α Cyg are displaced towards shorter wavelengths. The cores are shifted by a velocity of −130 km/s and reach a depth of 85 %. The lines are very wide: at a depression of 60 % they extend from −350 to +50 km/s. This is considerably wider than can be explained by microturbulence. The width of the lines is probably due to a radial velocity gradient. The presence of such a gradient is also suggested by the shift of the resonance lines with respect to the other lines.

A similar wavelength shift is observed in the Fe II resonance line at 2585.9 Å. The core of this line is displaced by about −120 km/s.

The escape velocity at the surface of α Cyg can be estimated from the study of this star by Groth (1961) and the star HD 33579 (A3–I0) by Wolf (1972). Assuming a mass of 25 $\mathscr{M}_{\odot}$ (HD 33579) and an acceleration of gravity of lg g = 1.13 (α Cyg) we find an escape velocity of 185 km/s and a radius of $R^* = 200\,R_{\odot}$.

The velocity of the short wavelength side of the linecores is larger than the escape velocity which indicates that α Cyg is losing mass. The visual spectrum of other A-type supergiants also shows evidence for mass loss which is probably one or two orders of magnitude smaller than in extreme OB-supergiants (Hutchings 1971). From the lack of resonance lines near the luminosity peak, Hutchings concluded that radiation pressure does not seem a likely driving mechanism for the mass loss in A-type supergiants.

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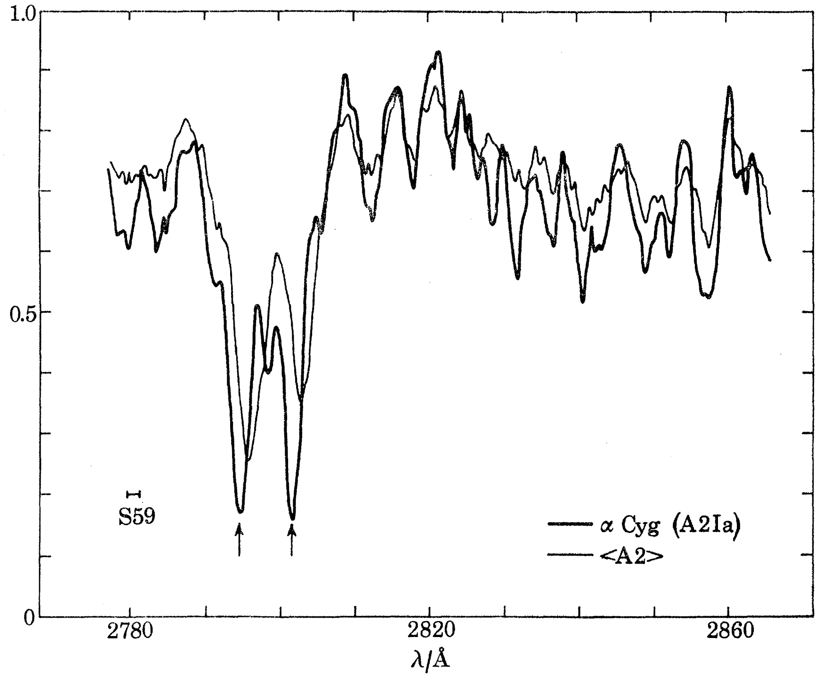

FIGURE 1. The S59-spectrum of α Cygni from 2775 to 2865 Å, compared with the corresponding spectrum of an average A2-star. The f.w.h.m. of the S59 instrumental profile is indicated.

2. Predicted profiles of the Mg II resonance lines in the expanding atmosphere of α Cyg

The profiles of the Mg II resonance lines in the expanding atmosphere of α Cyg were computed, using the theory of Lucy (1971). The computations were made with the following assumptions:

(i) The lines are formed by scattering which is coherent in the frame of the moving atmosphere.

(ii) The thermal velocities are neglected with respect to the flow velocities.

(iii) The ionization equilibrium is determined by radiative ionization and recombination.

The first assumption has been criticized by Caroff, Noerdlinger & Scargle (1972), who showed that thermal motions can play an important role in the shape of the redistribution profiles. However, the assumption seems to result in a reasonable description of the line profile, except for the emmision peak. The second assumption is evidently not justified in the deeper layers where the expansion starts and which contribute significantly to the line profile near the laboratory wavelength λ_0. Consequently we should be aware that we cannot expect to predict the profile near λ_0 correctly. The third assumption is probably valid throughout the expanding atmosphere where the electron density $n_e < 10^{11}$ cm^{-3}. This can easily be checked by means of the expressions for the ratio between the photo-ionization rate and the collisional ionization rate given by Böhm (1960, p. 101).

The density ρ at any height h above the photosphere was computed by means of the equation of continuity:

$$-\mathrm{d}M/\mathrm{d}t = 4\pi R^{*2}x^2\rho(x)v(x),$$

where $-\mathrm{d}M/\mathrm{d}t$ is the rate of mass loss and $x = 1+h/R^*$. The rate of mass loss was taken as a free parameter in the computations.

Two types of velocity functions $v(x)$ were considered:

$$v_1(x) = v_t\sqrt{(1-(1-\alpha)/x-\alpha/x^2)}$$

and

$$v_2(x) = v_0(x-1).$$

For values of $-1 < \alpha < 1$ the function $v_1(x)$ increases rapidly from $v = 0$ at the photosphere to $v = v_t$ in the outer layers. The velocity functions used in this study are shown in figure 2.

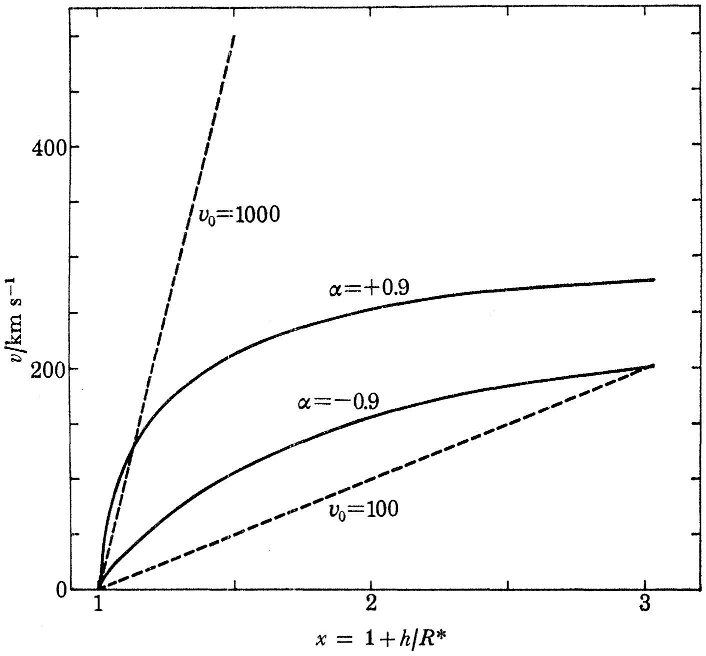

FIGURE 2. The velocity against height relations used in this study.
——, $v_1(x) = v_t\sqrt{(1-(1-\alpha)x-\alpha/x^2)}$ with v_t = 300 km/s;
– – –, $v_2(x) = v_0(x-1)$, parameter v_0 (km/s)

The ionization equilibrium was computed at any height by means of the relation given by Strömgren (1948).

$$\frac{n(Mg^{2+})n_e}{n(Mg^+)} = 5.0\times10^{15}(W2g^{2+}/g^+)\,T_e^{\frac{1}{2}}\,T_r\exp(-\chi/kT_r).$$

The geometrical dilution factor $W = \frac{1}{2}(1-\sqrt{(1-(1/x)^2)})$. The statistical weights of the ground levels are $g^{2+} = 1$ and $g^+ = 2$ and the ionization potential $\chi = 15.03$ V. The electron density was derived from ρ by assuming $n_e = n_H + n_{He}$ and $n_{He}/n_H = 0.10$.

An electron temperature of $T_e = 7000$ K was adopted, which is the boundary temperature of the static model for α Cyg computed by Groth (1961).

The most critical parameter in the ionization equilibrium is the radiation temperature T_r at the wavelength below the ionization limit, i.e. at $\lambda \lesssim 825$ Å.

A reduction of the flux at $\lambda \approx 800$ Å by a factor Q would have the same effect on the density of the Mg^+ ions and on the computed line profiles as an increase of the rate of mass loss by the same factor Q. For this study we adopted $T_r = 6000$ K. The effect of this assumption will be described in the next section.

For the computations of the Mg II profiles, we adopted an abundance of $Mg/H = 3\times10^{-5}$

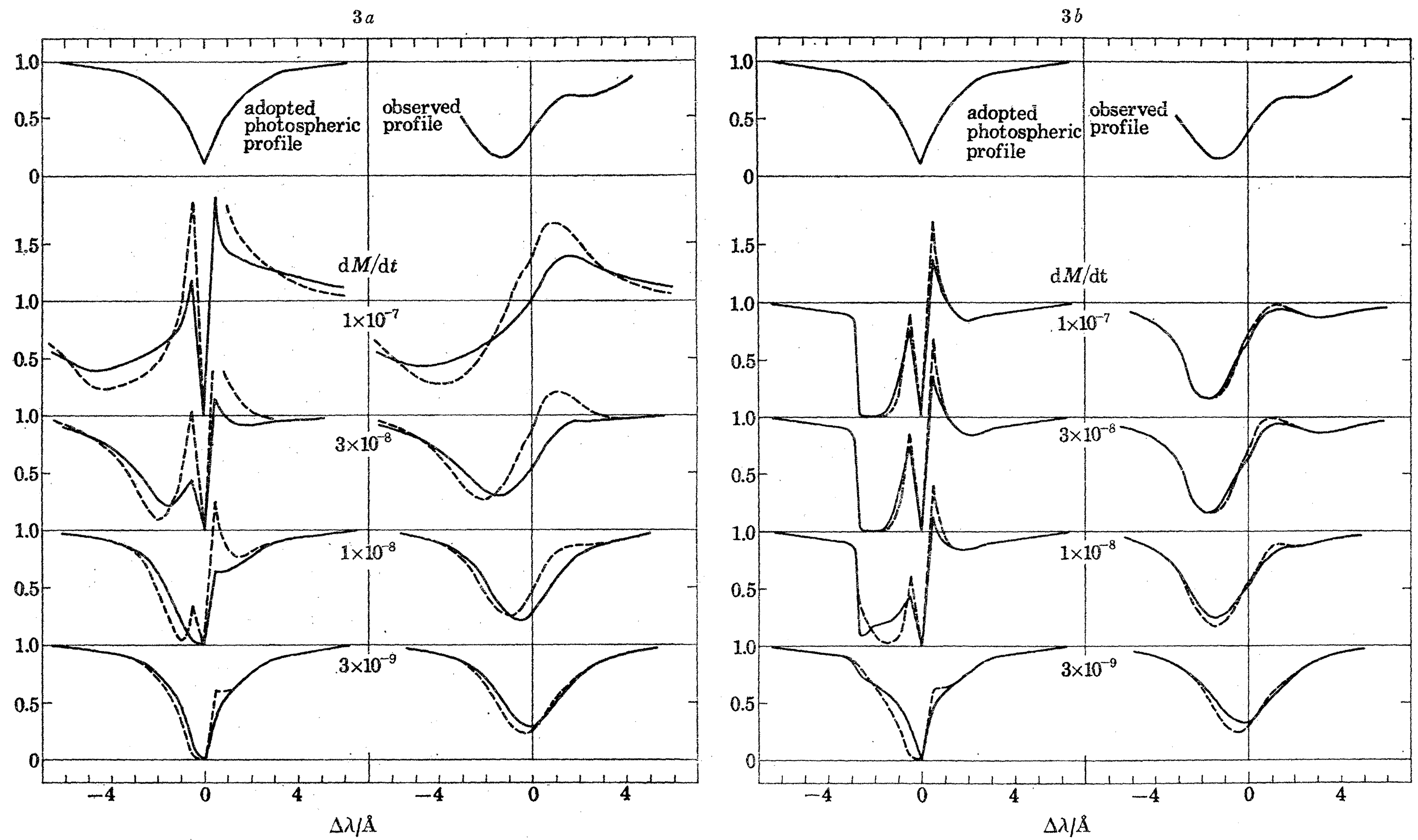

FIGURE 3. The predicted profiles of the Mg II resonance lines in an expanding atmosphere. The upper parts show the adopted photospheric profile and the observed profile. The left hand lower parts show the predicted profiles for four rates of mass loss. The right hand lower parts show these profiles after convolution with the instrumental profile.

FIGURE 3a: $v = v_0(x-1)$; ——, $v_0 = 1000$ km/s; – – –, $v_0 = 100$ km/s.

FIGURE 3b: $v = v_t\sqrt{(1-(1-\alpha)/x-\alpha/x^2)}$ with $v_t = 300$ km/s; ——, $\alpha = 0.9$; – – –, $\alpha = -0.9$.

(Lamers, van der Hucht, Snijders & Sakhibullin 1973). The absorption profile of the underlying photosphere was computed by M. Snijders using the static model atmosphere of α Cyg from Groth (1961) and an l.t.e. theory of line formation. We allowed for possible non-l.t.e. effects in this profile by increasing the depth of the linecore to 90 %.

The resulting predicted profiles are shown in figure 3*b* for $v_1(x)$ with $v_t = 300$ km/s, and in figure 3*a* for $v_2(x)$ with $v_0 = 100$ and 1000 km/s. The left hand side of both figures shows the predicted profiles for various rates of mass loss and two values of α (figure 3*b*) or two values of v_0 (figure 3*a*). The sharp dip at $\Delta\lambda = 0$ represents the interstellar component with an equivalent width of $W_\lambda = 0.500$ Å, which is superimposed on the predicted line. This value was estimated by means of the empirical relation between the equivalent width of the interstellar Mg II lines and the distance of the star (Lamers & Snijders 1975).

The right hand sides of the two figures show the predicted profile, convoluted with the S-59 instrumental profile. These convoluted profiles can be compared directly with the observed profile shown in the top part of the figures.

3. Discussion and conclusions

In comparing the predicted and observed profiles, the limitations of the predictions should be kept in mind. The neglected thermal velocities and the estimated interstellar components may introduce errors in the linecentre near λ_0. The wings of the observed profiles may contain blends from other ions. Consequently, the comparison should concentrate on the profile in the region $-3 \lesssim \Delta\lambda \lesssim -1$ Å.

The underlying photospheric profile was computed with a hydrostatic model atmosphere. This model is probably sufficiently accurate for the line wings which are formed in the deeper layers. The core of the line, however, is formed in the layers where the hydrostatic model is no longer correct. Test computations with shallower cores of the photospheric line resulted in too shallow profiles.

From the comparison between the predicted and observed profiles we can draw the following conclusions:

(i) The profiles predicted with the velocity function $v_1(x)$ (figure 3*b*) agree better with the observations than those with $v_2(x)$ (figure 3*a*). This suggests that the expansion is due to some outward directed acceleration which is effective in the lower parts of the expanding atmosphere only and accelerates the flow up to a velocity of about 300 km/s. We also computed profiles with $v_t = 200$ and 400 km/s but these do not agree with the observations.

(ii) The best agreement between the profiles of figure 3*b* and the observations is reached for rates of mass loss of $1 \times 10^{-8}\ \mathscr{M}_\odot$/year or larger. For rates larger than $1 \times 10^{-8}\ \mathscr{M}_\odot$/year the lines become optically thick and the profiles are sensitive to the velocity law only and not to the rate of mass loss.

The derived lower limit for the rate of mass loss depends critically on the adopted radiation temperature T_r. Groth (1961) derived a value of $T_{eff} = 9170$ K and lg $g = 1.13$ for α Cyg. The blanketed model atmosphere of $T_{eff} = 9000$ K and lg $g = 2.0$ from Kurucz, Peytremann & Avrett (1972) which shows about the same visual flux distribution as Groth's model, has a radiation temperature at 810 Å of $T_r = 5240$ K. Consequently, the derived rate of mass loss which was computed by assuming $T_r = 6000$ K should be scaled down by a factor of about 10–70, depending on the Mg^{2+}/Mg^+ ionization ratio. On the other hand, the study of Mihalas

& Hummer (1974) indicates that extended model atmospheres may have a considerably larger far-u.v. flux than normal models.

From these considerations we conclude that the rate of mass loss in α Cyg of probably larger than about $3\times10^{-10}\,\mathcal{M}_{\odot}$/year.

The radiation pressure due to the two Mg II resonance lines produces an outward directed acceleration

$$g_r = \frac{2\pi}{c}\frac{\mathcal{F}(\nu_0')}{x^2}\frac{1-e^{-\tau_1}}{\tau_1}$$

(Lucy 1971), where $\mathcal{F}(\nu_0')/x^2$ is the photospheric flux as seen by the flow at a height x with a velocity $v(x)$. The modified optical depth τ_1 depends on $v(x)$. The values of g_r are listed in table 1 for various rates of mass loss and height.

These rates of mass loss refer to the situation with $T_r = 6000$ K and should therefore be decreased by a factor of about 30 if $T_r = 5240$ K.

Table 1. The acceleration g_r (cm/s^2) produced by the two Mg II resonance lines in the models with the $v_1(x)$ velocity function and $v_t = 300$ km/s

dM/dt ($\mathcal{M}_{\odot}$/year)	3×10^{-9}		1×10^{-8}		3×10^{-8}	
	$\alpha = 0.9$	-0.9	0.9	-0.9	0.9	-0.9
$x = 1.1$	7.8	3.8	11.5	1.2	4.3	0.4
$x = 1.5$	4.3	5.0	7.7	3.8	4.1	1.3
$x = 2.0$	2.5	3.1	4.6	4.1	2.2	1.5

The data in this table show that the Mg II lines produce an acceleration of the same order of magnitude as the gravitational acceleration. The near ultraviolet spectrum of A-type stars contains a large number of resonance lines of singly ionized metals, like Mg II, Fe II, Cr II and Mn II. The radiation pressure produced by these lines may be responsible for the mass loss in A-type supergiants. It would be interesting to apply Lucy & Solomon's (1970) theory to these stars.

A study of the near-u.v. resonance lines of singly ionized metals in A-type supergiants based on high resolution spectra will greatly improve our knowledge on the process of mass loss in these stars.

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