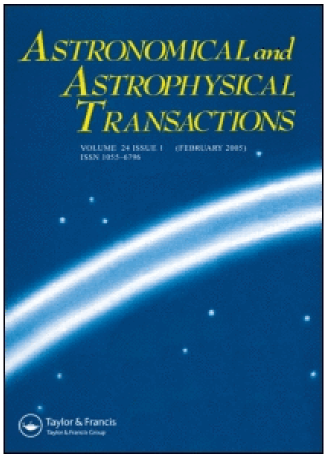

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New insights on late-A and early-F star activity

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NEW INSIGHTS ON LATE-A AND EARLY-F STAR ACTIVITY

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The onset of chromospheric activity in late-A and early-F stars is here discussed. The detection of Ly-α emission core in several A and F atars with the *IUE* satellite, gives evidence for the presence of chromospheric layers in these stars up to $B - V = 0^m\!.19$ (Marilli *et al.*, 1996). Semi-empirical chromospheric models for Altair allowed us (Freire Ferrero *et al.*, 1995) to explain the observed emission profiles taking into account normal H I interstellar (IS) absorption. However, due to the very high rotational velocity, we analysed alternative hypotheses to explain the observed emissions: (1) circumstellar or shell matter; (2) co-rotating expanding optically thin wind. We ruled out these hypotheses because their effects are negligible and as a consequence, this result reinforces the chromospheric origin of the observed Ly-α core in Altair. The stars of our sample, having observed Ly-α profilies similar to Altair's and similar stellar and IS properties, should reproduce similar chromospheric behaviour. Here we discuss several important questions that are raised by these results.

KEY WORDS Stellar activity, A and F stars, Ly-α, interstellar H I

1 INTRODUCTION

The presence of chrospheric layers in the outer atmospheres of late-type stars, requires that the plasma above the photosphere is heated by non-radiative processes. Acoustic and magnetic heating processes, which are commonly supposed to be responsible for the non-thermal energy deposition, both need the presence of a convective zone in the subphotospheric layers. Therefore, the precise location of the onset of chromospheric emission in the H-R diagram is of the great importance in the study of stellar structure because it should mark the boundary for the onset of convection. With this aim we have undertaken a spectroscopic study of the hydrogen Ly-α; using the *IUE* spectrograph in high-resolution mode (Freire Ferrero *et al.*, 1990; Catalano *et al.*, 1991; Marilli *et al.*, 1992).

2 OBSERVATIONS AND ANALYSIS

We have obtained 13 spectra of eight A–F stars with the SWP camera of *IUE*. The *IUE* archive has been searched for spectra of A–F stars with exposure times long enough to show some signal in the Ly-α region. The stellar parameters and characteristics of our sample are given in Table 1.

Table 1. Data on observed stars

Star	*Name*	*Sp. type*	*V*	*B − V*	$v \sin i$ ($km\ s^{-1}$)	*SWP*	*Exp. time* (*min.*)	*Remark*
HD 97603	δ Leo	A4IV	2.56	0.12	181	46745	434	δ Sc? VB
HD 11636	β Ari	A4V+G0V	2.64+5.5	0.13+0.58	79	46758	465	SB
HD 39060	β Pic	A6V	3.85	0.17	139	37699*	600	shell star
HD 187642	Altair	A7V-IV	0.77	0.22	220	3427	100	
						23043*	250	
						31045	120	
						31046	120	
HD 203280	α Cep	A7IV-V	2.44	0.22	245	30259	313	δ Sc?
						41615	450	
HD 76644	ι *UMa*	A7IV	3.14	0.19	151	41612	400	SB
						41613	420	
HD 127762	γ Boo	A7IV/III-IV	3.03	0.19	139	10885*	434	δ Sc
HD 12311	α Hyi	F0III-IV	2.86	0.28	153	41614	315	
						45023	410	
HD 141891	β TrA	F0IV	2.85	0.29	90	30268	425	VB
HD 432	β Cas	F2III	2.27	0.34	70	24127*	185	δ Sc VB
						32002*	500	
HD 45348	α Car	A9II	−0.72	0.15	–	46759	80	

Note. *Spectra from the *IUE* archive.

Owing to the low flux level expected for these stars at Ly-α wavelengths, long exposure times were needed, implying the development of a strong geocoronal Ly-α emission superposed on the stellar spectra. We used different methods to eliminate the geocoronal emission and to obtain reliable background corrections. These methods have been described in detail elsewhere (Freire Ferrero *et al.*, 1990; Catalano *et al.*, 1991).

The corrected spectra show two emission peaks as a result of the superposition of the saturated IS H I line absorption over the stellar line core emission. This situation can be modeled, in a simple way, by a gaussian emission (for the stellar line-core)

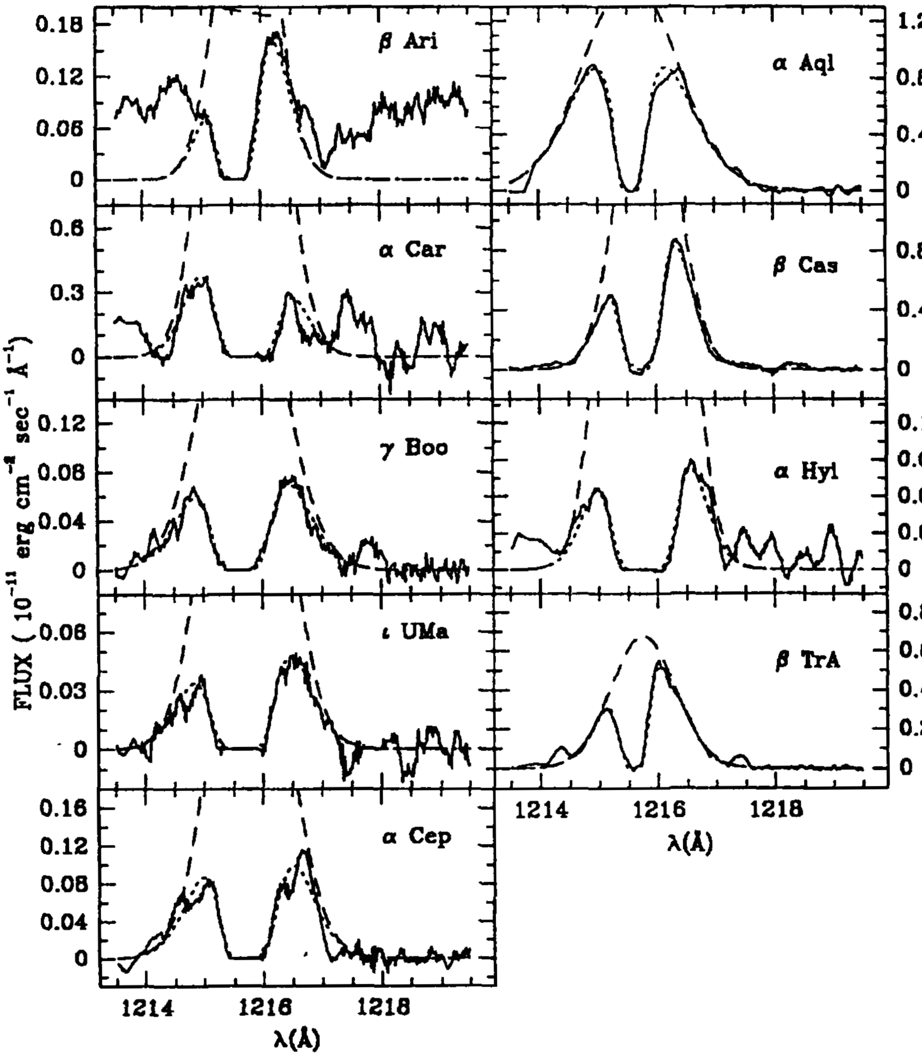

Figure 1 Observed and modelled Ly$_\alpha$ emission profiles. The dashed line is the assumed gaussian stellar profile. The dotted line represents the fitting profile, including the interstellar H I and D I absorption.

overlaid by a lorentzian absorption (for the IS H I line profile). The computed profiles using this simplified model fit very well the observed Ly-α profiles and give IS column densities in agreement with values in the literature (γ Boo, Marilli *et al.*, 1992; Altair, Freire Ferrero *et al.*, 1995; other stars, Marilli *et al.*, 1996). In addition, detailed NLTE calculations, including partial redistribution of Ly-α for Altair confirmed that the IS column densities deduced in this way were of the same order as those deduced from the simplified model (Freire Ferrero *et al.*, 1995).

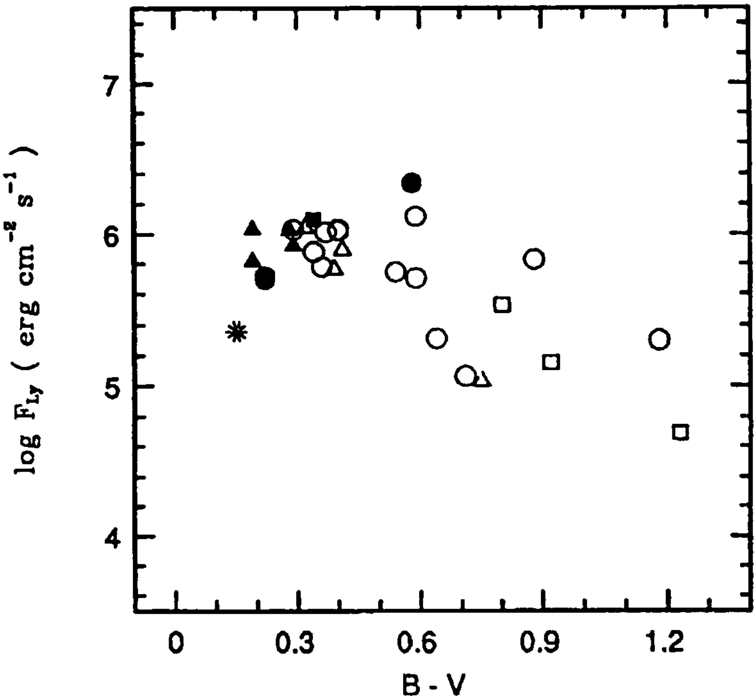

Figure 2 Ly α surface flux vs. $B-V$. Stars in Table 2 are plotted with filled symbols, save the supergiant α Car (*). Different symbols refer to: main sequence (o), subgiants (△) and giants (□).

We used the simplified model to make a preliminary estimate of the stellar energy released in the Ly-α line. The modelling procedure consisted of minimizing the χ^2 goodness-of-fit of a six-parameter function defined by two theoretical profiles: a gaussian emission profile, with the peak intensity and σ as free parameters, and a Voigt absorption profile for the IS H I and D I with the H I column density, the velocity dispersion and the bulk velocity as free parameters. In Figure 1 the observed profiles are overlaid with the computed profiles. The figure clearly shows that the overall computed profiles agree fairly well with the observed ones, supporting the proposed model. The resulting luminosities and integrated fluxes at the Earth and at the stellar surface, as well as the adopted distances and the IS hydrogen densities, are listed in Table 2.

The plots in Figure 1 clearly show that Ly-α emission is visible in the spectra of many stars, but in some cases the detection is very marginal, or even questionable. However, we have detected Ly-α emission in stars as early as A7 ($B-V=0.19$) establishing a new limit for the presence of a chromosphere.

The derived surface flux together with the values determined from low-dispersion *IUE* spectra (Bruno *et al.*, 1991, private communication) and values taken from the literature, are plotted in Figure 2 as a function of $B-V$. The plot is characterized

Table 2. Ly-α emission flux parameters and the H-interstellar absorption

Star	*d* (*pc*)	$f(10^{-11})$ ($erg\,cm^{-2}\,s^{-1}$)	*S/N*	*FWHM* (*Å*)	$log\,F$ ($erg\,cm^{-2}\,s^{-1}$)	$log\,L_{Ly}$ ($erg\,s^{-1}$)	l_{II}	b_{II}	$log\,NH$ (cm^{-2})
β Ari	13.5	0.51*	1.	1.06 ± .2	6.34	29.04	142.74	−39.68	18.60 ± .1
Altair	5.	3.01	12.2	1.88 ± .05	5.697	28.94	47.74	−8.91	18.35 ± 0.0
α Cep	14.7	0.68	2.1	1.41 ± .15	5.72	29.25	101.0	9.17	19.00 ± .1
ι *UMa*	13.3	0.41	1.	1.36 ± .2	5.82	28.94	171.51	40.84	19.15 ± .1
γ Boo	$29.^{+}$	0.45	1.1	1.53 ± .12	5.82	29.66	67.26	66.17	19.00 ± .1
α Hyi	20.8	1.13		1.18 ± .15	6.03	29.77	289.45	−53.76	19.25 ± .1
β TrA	12.0	0.93	11	1.29 ± .12	5.93	29.21	321.85	−7.52	17.60 ± .05
β Cas	13.9	2.77	9.4	1.13 ± .15	6.10	29.81	117.52	−3.27	18.60 ± .05
α Car	35.7	4.39	1.	1.18 ± .15	5.36	30.83	261.21	−25.29	19.20 ± .1

Note. *Attributed to the G0 component.

by an increasing trend, that seems to stop at $B - V \approx 0.5$ where the flux values start to be more clustered revealing a negligible or non-existent dependence on stellar rotation. This change may be related to the decline in the X-ray and in EUV luminosities for $B - V < 0.5$. On the other hand, the efficiency of the dynamo mechanism can be tested from the degree of correlation between the rotation rate and the coronal/chromospheric rate emission, so the very small spread of Ly-α flux in Figure 2 for $B - V < 0.5$ does support the suggestion that the correlation stops at this spectral type, and that the emission may be exclusively associated with heating by acoustic flux.

3 CHROMOSPHERES OF A–F STARS

Although the X-ray emission in Altair and in some other stars of our sample does suggst a solar-like chromospheric/transition-region/coronal structure, this region explanation is not conclusive. The possible absence of magnetic energy, the fast rotation and a suspected wind could produce non-solar atmospheric structures.

With the aim of investigating the importance of these effects, we have started to build atmospheric models of these stars using the Ly-α and Mg II lines. Chromospheric modelling of Altair (Freire Ferrero *et al.*, 1995) shows that a steep temperature rise joining the photospheric component and the chromospheric plateau best reproduces the observed profiles. Testing a grid of integrated mass column and plateau temperature parameters (log m_0, T_p) we find that the best agreement with observations lies around log $m_0 = -3.8$ and $T_p = 9000$ K.

However, the calculated profile always has higher fluxes than the observed one (Figure 3, upper panel). It appears that this kind of semi-empirical model provides a better fit to the observations, both in the slope of the emission shoulders and in the intensity of the feet, if the condition of equality between the photospheric and chromospheric $v \sin i$ can be relaxed (i.e. if differential rotation can

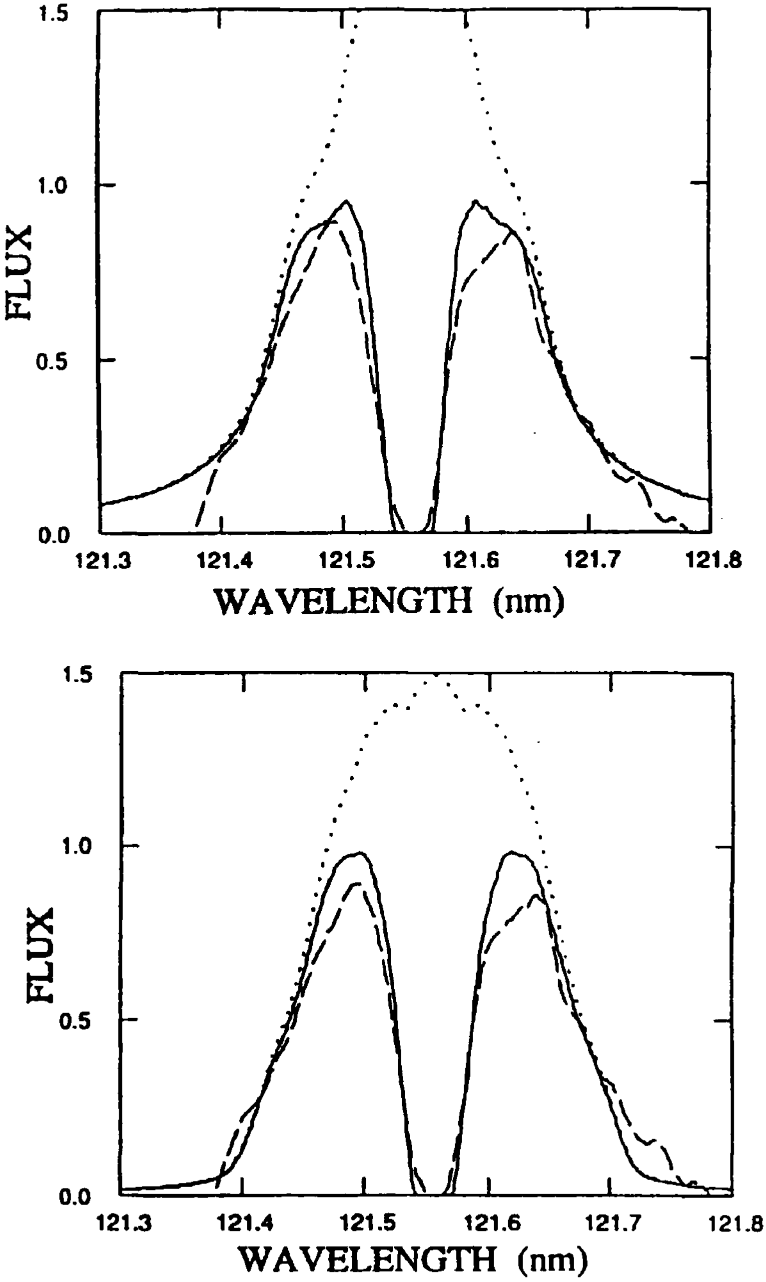

Figure 3 The observed Ly-α core (dashed line) compared to the computed profiles (dotted lines) for two different chromospheric models and including the interstellar Ly-α absorption. On both models a micro-turbulent velocity $\xi = 10$ km s^{-1} was assumed. Upper panel: chromospheric model defined by $T_p = 9000$ K, $\log m_0 = -3.8$, $v \sin i = 220$ km s^{-1}. Lower panel: chromospheric model defined by $T_p = 20\,000$ K, $\log m_0 = -4.7$, $v \sin i = 320$ km s^{-1}.

be assumed). In particular, an atmospheric model with a chromospheric plateau of $T_p = 20\,000$ K and a column mass density $\log m_0 = -4.7$ with a chromospheric $\nu \sin i = 320$ km s^{-1} matches better the observed profile (Figure 3, lower panel). Such high $v \sin i$ values could be attained near the stellar equator, but we would then have to accept that the Ly-α emission core is formed only in the equatorial region and that there is a strong oblateness of the stellar disk.

However, due to the very high rotational velocity, two other alternative hypotheses should be investigated to explain the observed emission.

Circumstellar or Shell Matter

Although the possibility of a circumstellar contribution to the interstellar Mg II features cannot be ruled out completely, this hypothesis is highly improbable due to the absence of other UV circumstellar lines arising from fine-structure levels in the ground configurations of Si II and Fe II. The absence of such circumstellar features might also imply a negligible circumstellar absorption for the Ly-α as well. Moreover, it can be considered as evidence that Altair is rotating at less than the critical velocity.

Co-rotating Expanding Optically Thin Wind

The observed Ly-α emission profile gives two main constraints:

(1) the emission FWHM implies a rotation velocity of the line formation region of ≈ 500 km s^{-1}, i.e. the line should form at $R \approx 2R^*$;

(2) the apparent lack of any wavelength shift at *IUE* resolution sets an upper limit of 50 km s^{-1} in the wind speed.

With these parameters, we estimate the optical depth at $R = 2R^*$ and the expected Ly-α luminosity if its emission would be produced in an expanding co-rotating wind.

Radio and Hα observations placed an upper limit of $10^{-10} M_\odot$ yr^{-1} for Altair's mass loss. In this case, if we have a co-rotating wind, then the Ly-α profile would be broader than observed. Moreover, the Ly-α would be formed in a coronal region, i.e. in a nearly completely ionized medium, which is inconsistent with the observed emission flux.

Ruling out these hypotheses on the basis of the negligible effects and the inconsistency with the observed Ly-α emission, the chromospheric origin of the observed Ly-α core in Altair, in a classical chromosphere, seems more likely.

Nevertheless the computed line profiles (see Figure 3) using semi-empirical chromospheric models, support two possible alternative scenarios for Altair's chromosphere:

(1) a classical chromosphere extending over the whole stellar disk, with differential rotation represented by a mean $\nu \sin i = 220$ km s^{-1} and an equatorial velocity only slightly higher, making Altair close to equator-on;

(2) a chromosphere filling only an equatorial zone, the stellar atmosphere showing differential atmospheric structure over the whole stellar disk due to pronounced differential rotation with an equatorial ratational velocity near the critical velocity.

In both cases, Altair should have an external atmospheric structure like the late-type stars, including a chromosphere (Ly-α emission line core), corona (X-ray corona), and probably a transition region.

4 CONCLUSION

The stars of our sample, having similar observed Ly-α profiles to Altair's and similar stellar and interstellar properties, should reproduce similar chromospheric behaviour. Several important questions are raised by these results:

(1) the influence of the high rotational velocity on the stellar structure (interior and atmosphere), i.e. on the convective subphotospheric layers, on differential rotation, etc;

(2) the complexity of chromospheric and coronal activity origin and the need to extend classical theories of stellar dynamos and acoustic energy generation;

(3) the need for more information about normal and abnormal stellar activity from UV, EUV and X-ray observations.

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