Peculiar Versus Normal Phenomena in A-Type and Related Stars
ASP Conference Series, Vol. 44, 1993
M.M. Dworetsky, F. Castelli, and R. Faraggiana (eds.)

SPECTRAL DIAGNOSES OF CHROMOSPHERES AND WINDS IN A–TYPE STARS

Thierry LANZ *)
NASA Goddard Space Flight Center, Code 681,
Greenbelt, MD 20771, USA

Ivan HUBENY
Universities Space Research Association, NASA/GSFC, Code 681,
Greenbelt, MD 20771, USA

ABSTRACT So far, neither chromospheres nor stellar winds have been directly detected in main-sequence A stars. While radiative diffusion requires extremely weak stellar winds to reproduce chemical anomalies (10^{-15} to $10^{-12} M_{\odot}\mathrm{yr}^{-1}$), two independent direct searches for mass loss set up upper limits to $10^{-10} M_{\odot}\mathrm{yr}^{-1}$, which is still several orders of magnitude higher. We discuss some new recent possibilities to detect chromospheres which arise thanks to new NLTE model atmospheres. In the near future, some progress is also expected from new observations of Lyman α with *HST* and from the increased sensitivity of *ROSAT* in the X-ray domain.

INTRODUCTION

During the last decade, a major progress was achieved towards an understanding of the physical conditions in the outer layers of stars across the HR diagram. On the main sequence, O and early B stars have been detected to possess strong winds with high mass loss rates ($\dot{M} > 10^{-9} M_{\odot}\mathrm{yr}^{-1}$). The Sun is the only late-type main-sequence star for which a wind is directly observed ($\dot{M} \simeq 2 \cdot 10^{-14} M_{\odot}\mathrm{yr}^{-1}$). On the other hand, cool stars (F and later type stars) have similar and sometimes stronger activity than the Sun, which is related to their magnetic field generated in their convective envelope. The A and late-B stars do show neither strong mass loss signatures nor solar-type activity, but a significant fraction of them exhibit chemical peculiarities. Our present knowledge therefore leads us to consider three basic types of atmospheres for single main-sequence stars.

In a radiative atmosphere, chemical elements may migrate under the competing effect of the radiation pressure and the gravity. The result of this diffusion is different for each species, some are predicted to leave the star, other to accumulate in layers, yielding various apparent chemical abundance anomalies. It appears that this process is very sensitive to the presence of a wind – even a very

---

*) NRC–NASA Research Associate

weak one – (see e.g. Michaud *et al.* 1987, Babel 1992), and diffusion calculations may benefit greatly from a better understanding of the structure of the outer layers. More generally, the A stars are in a key position between the hot and the cool stars and thus may provide essential clues on the energetics and the dynamics of stellar outer layers.

In the cool stars, the (electron) temperature in the atmosphere decreases towards the exterior until it reaches a minimum, and then raises again due to non-thermal phenomena. These regions are traditionally called stellar *chromospheres* and *coronae*. There is still no consensus for hot stars, but there is an indication that some layers in the wind might have very high temperatures (Conti & Underhill 1988). Signatures of chromospheres are typically emissions or reversals in the cores of strong resonance lines (Mg II, C II, Ca II), while coronae with $T \approx 10^6$ K are detected by an X-ray emission. Resonance lines of super-ionized species are formed in the transition region between the chromosphere and the corona. If such transition regions exist in A stars, they may be diagnosed from the C IV, Si IV or He II absorptions, since these ions are not present in the photosphere. Following the claim by Pallavicini *et al.* (1981) that Vega and Sirius are X-ray emitters, the search for chromospheres in A stars has attracted much attention some ten years ago, and was fuelled by the opportunity to obtain high-resolution far-ultraviolet spectra with *Copernicus* and the *International Ultraviolet Explorer*. Later on, Golub *et al.* (1983) and Schmitt *et al.* (1985) showed that *Einstein* and *EXOSAT* observations of single A stars failed to reveal any convincing X-ray emission, with the notable exception of α Aql (A7V). At the same time, searches of line asymmetries from *IUE* spectra showed that the strong wind gradually disappears around the spectral type B1 on the main sequence (Cassinelli & Lamers 1987); but spectra with high signal-to-noise ratios open new opportunities to observe weak stellar winds.

We discuss in this paper the attempts to find chromospheres and winds in A stars, with a focus on the main-sequence stars and the underlying interest of CP stars. It is now time for a closer look, since we expect much better observations to be available soon from the *Hubble Space Telescope* and *ROSAT* and since new model atmospheres (see Hubeny & Lanz, these proceedings) will allow to check how adequate radiative and hydrostatic equilibria are for A stars.

CHROMOSPHERES IN A-TYPE STARS?

Reversals in the core of the Ca II K line are the most characteristic signatures of the chromospheric activity in cool stars. Freire-Ferrero *et al.* (1977, 1978) did not observe any emission in the core of the Ca II resonance lines in the high-resolution spectra of 4 bright A stars (including α Aql). Dravins (1981) observed 8 A stars in clusters with similar results, and therefore supported the idea that A stars do not show any reversal in the core of the K line. Nevertheless the absence of this typical signature does not rule out the possibility of a temperature rise above $\log \tau_{5000} \leq -4$, because the core of the Ca II lines is formed deeper. Only strong resonance lines in the Balmer continuum may probe such upper layers. *Copernicus* high-resolution spectra of α Lyr also do not show any emission neither in the C II λ1335 and in the Si II λ1307 lines (Freire-Ferrero 1979) nor in Lyman α (Praderie 1981). The Mg II h and k lines are the primary ultraviolet indicators of the chromospheric activity, and accordingly these lines have been used to diagnose chromospheres in a wide range of stellar types. Böhm-Vitense & Dettmann (1980) and Blanco *et al.* (1982) found that the chromospheric activity disappears for spectral types earlier than F0. Seggewiss (1990) pointed out that the late Ap stars do not show chromospheric activity, analogously to the normal A stars. Freire-Ferrero *et al.* (1983, 1987) undertook detailed studies of the Mg II h and k lines, including partial redistribution, in Vega and Sirius. As the line cores are formed at very small optical depths, they had to arbitrarily choose the temperature structure in these layers, adopting either a temperature plateau with a low temperature (e.g. $T = 6000$K) or a chromospheric-like temperature rise. They did not find any conclusive evidence for a chromosphere in these two stars.

In addition to the lack of X-ray detection in single A stars and the apparent absence of a corona, there is no evidence of superionization in their ultraviolet spectrum. In the late A stars, emission lines formed in the transition region between the photosphere and the corona (C IVλ1550, Si IVλ1400, He IIλ1640) do not show up (Crivellari & Praderie 1982). Moreover, the absorption features at the wavelength of these lines are observed in the spectrum of late B and early A stars, but Hubeny *et al.* (1985) and Freire-Ferrero (1986) showed that these absorptions are blends of numerous metallic lines (mainly Fe II and Fe III).

Models of the upper atmosphere

Since the studies of Freire-Ferrero, much progresses have been done to model the outer layers of A stars. Hubeny & Lanz (these proceedings) constructed a series of NLTE model atmospheres to investigate the influence of lines on the surface temperature. We should stress here that the latest models include a complete treatment of Lyman lines, while all previous modeling efforts for late B and A stars have assumed that Lyman lines are in detailed radiative balance. Although this assumption is valid in the "classical" photosphere, it certainly breaks down in the uppermost layers above $\log m \approx -6$. Hubeny & Lanz have shown that the Lyman lines are responsible for a strong cooling in the upper layers. The temperature structure of the NLTE model atmosphere, including all hydrogen lines, C I, and the C II, Mg II and Fe II resonance lines, is displayed in Fig. 1. We also show in this figure where the cores of these strong lines, as well as the Lyman and Balmer continua (just above the thresholds), are formed. These lines are formed very high in the atmosphere, and accordingly the line cores cannot be calculated correctly with a model atmosphere taking the first depth at τ_{5000} larger than 10^{-5} (such as Kurucz models)! The Lyman lines, and the C II and Mg II resonance lines, are indeed the best tools to diagnose the uppermost layers. While the cores of Hα, Hβ, and the Fe II resonance lines are sensitive to departures from LTE, they would be useful as chromospheric indicators only if the temperature rise starts deep enough.

The model atmospheres constructed by Hubeny & Lanz assumed the hydrostatic and the radiative equilibrium. It is likely that these two assumptions may break down at some point. However, we can now consistently predict the emergent spectrum from these models, especially the line cores of the strong resonance lines. A comparison with observational data will then show the adequacy of the assumptions.

To test how sensitive might this comparison for different lines be, we have constructed a semi-empirical model with a chromospheric temperature rise. We have assumed the same temperature structure in the deep layers as our NLTE

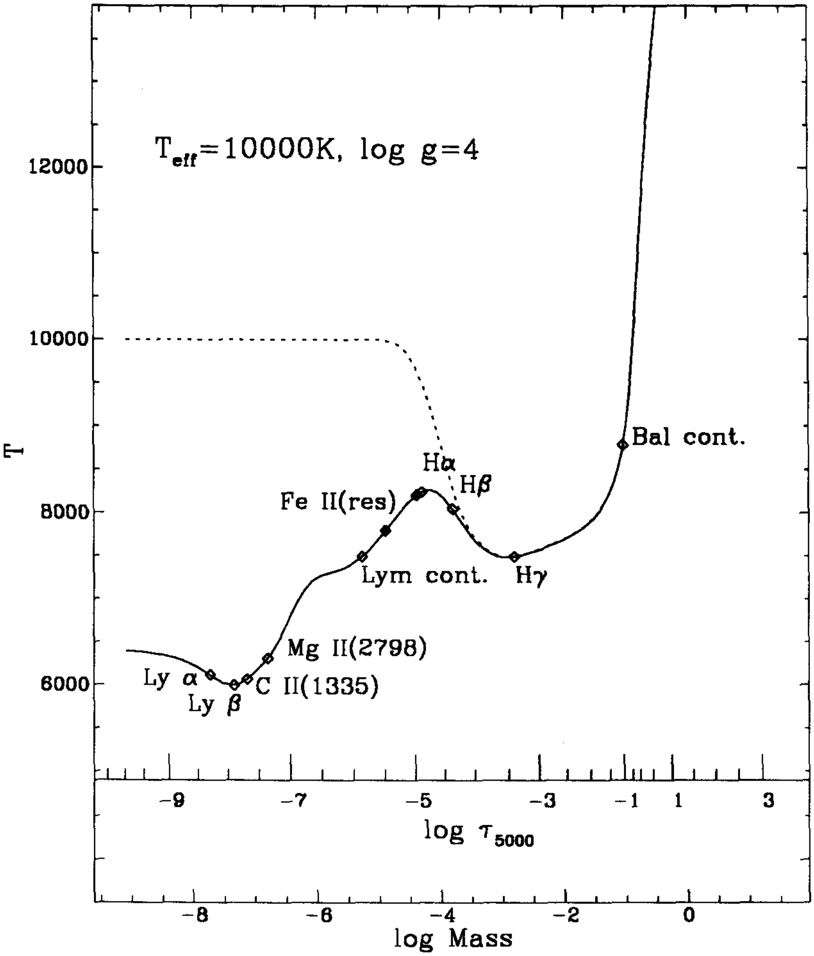

Fig. 1. Temperature structure and depths of formation of some transitions for a NLTE line-blanketed model atmosphere with $T_{\rm eff} = 10000$K, $\log g = 4$. The filled diamonds show the depth of formation at the frequencies of the maximum of the Fe II ODF's, which represents the cores of the Fe II resonance lines. The dashed line is the temperature stratification of a semi-empirical model with a chromospheric temperature rise.

models, a temperature plateau at the surface with $T = T_{\rm eff} = 10000$K, and a temperature rise at $\log m \approx -4$, as illustrated in Fig. 1. We have then calculated the emergent spectrum around Lyα, Hα, C IIλ1335 and Mg IIλ2798 for these two model atmospheres. The theoretical spectra were convolved with a rotational profile ($V_{\rm rot} = 20$ km·s^{-1}), and with an instrumental profile similar to the profile

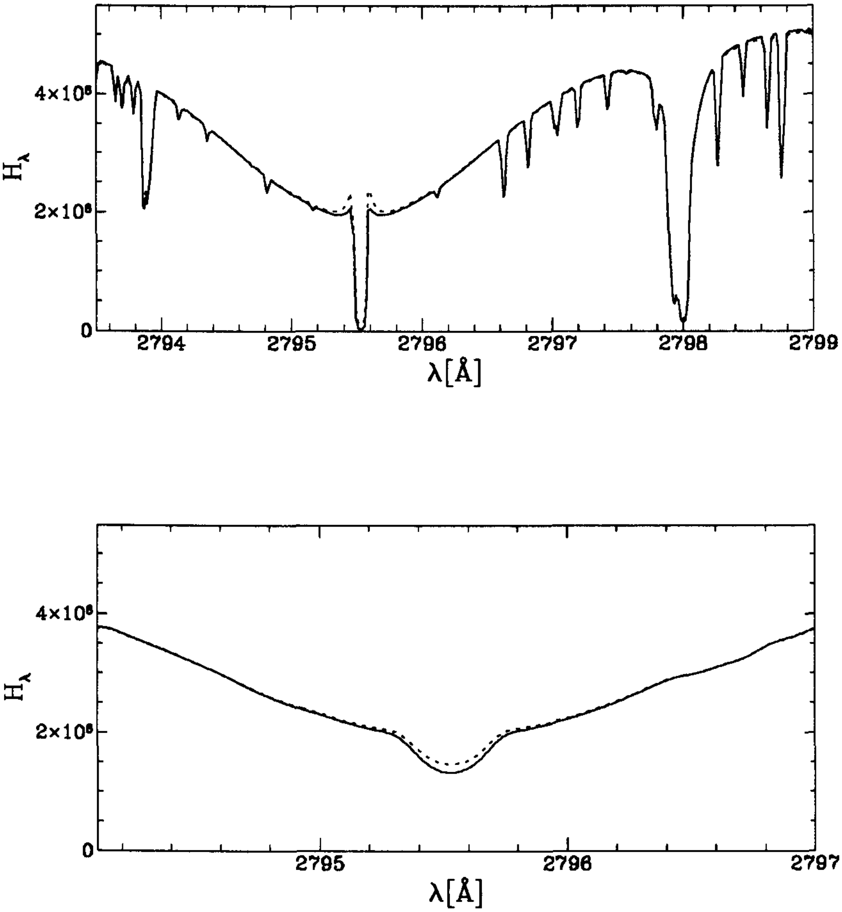

Fig. 2. Mg II k line profiles calculated for the NLTE model atmosphere (full line) and the semi-empirical model with a chromosphere-type structure (dashed line) displayed in Fig. 1. In the bottom panel, the theoretical line profiles (top panel) are shown after a convolution typical of observing conditions (see text).

of the high-resolution mode of *IUE* to mimic typical observational conditions (but no noise added!).

The cores of Hα and of the C II resonance lines show only very tiny differences between the two models. The results for the Mg II k line are presented in Fig. 2. We have assumed complete frequency redistribution, although Freire-Ferrero *et al.* (1983) showed that partial redistribution should be taken into account in order to reproduce the observed profiles of Sirius and Vega. The computed line profile shows a central reversal with a narrow absorption core. This reversal is almost entirely washed out by the rotational and instrumental convolutions, but the flux difference of up to 10% (about 2% of the continuum flux) continues to exist in the line core. Such a difference cannot be detected with a limited spectrophotometric accuracy of *IUE*, but it is well within reach of the Goddard High Resolution Spectrograph aboard *HST*. Finally, we note that no differences are seen in the Mg II subordinate lines, since they are formed around $\log m \approx -3$.

The Lyman α line core region is displayed in Fig. 3. Only the very core of the line is shown in the figure. In this case, we have furthermore considered a contribution of the interstellar absorption. We have assumed the hydrogen column density of 10^{18} cm^{-2}, a typical value for nearby stars (Bruhweiler & Vidal-Madjar 1987), which causes the predicted reversal almost to disappear. This suggests that, although the differences in the predicted profiles are the largest, using the Lyman α line as a chromospheric indicator may be more delicate than originally hoped. Since we could now incorporate consistently the Lyman lines in NLTE model atmospheres, the Lyman α line may be the best tool to study both the stellar outer layers and the interstellar absorption, provided we are able to separate these two contributions.

SEARCH FOR STELLAR WINDS IN MAIN-SEQUENCE A-TYPE STARS

In recent years, several workers have argued that the main-sequence A stars should lose mass at a small rate. Michaud & Charland (1986) pointed out that the radiative diffusion alone cannot explain simultaneously the metal-rich Am stars and the metal-deficient λ Bootis stars. An additional physical process must be invoked to explain these different abundance patterns. They suggested that a weak wind may change drastically the surface abundances: mass loss rates of the order of $10^{-15} M_{\odot} \mathrm{yr}^{-1}$ are appropriate for Am stars, while the metal underabundances observed in λ Bootis stars may be related to a stronger mass loss of about $10^{-12} M_{\odot} \mathrm{yr}^{-1}$. However, recent studies seem to suggest that it is rather a gas-dust separation in the proto-stellar cloud that may cause the observed underabundances (Holweger 1992, and these proceedings). Michaud *et al.* (1987) showed that the early B-type He-rich stars should have mass loss rates as small as $10^{-12.5} M_{\odot} \mathrm{yr}^{-1}$ to allow an helium enrichment by chemical separation. They found that the maximum mass loss rate for which separation can occur in main-sequence stars is about 10 times larger. Rotational modulation of the C IV and Si IV resonance lines in the He-peculiar stars (e.g. Shore *et al.* 1987) suggests that the wind in these stars is controlled by the magnetic field and that the mass loss occurs at the magnetic poles. Babel (1992, and these proceedings) showed that a weak inhomogeneous mass loss is also required to explain the distribution of chemical elements over the surface of the magnetic A2p SrCrEu star 53 Cam. The required mass loss rate at the magnetic poles is about $10^{-14.5} M_{\odot} \mathrm{yr}^{-1}$, while the separation and thus chemical anomalies are prevented by mass loss rates larger than $10^{-12} M_{\odot} \mathrm{yr}^{-1}$. These mass loss rates are much lower than the prediction of the radiatively-driven wind theory developed for OB stars and extrapolated to A stars. Linsky *et al.* (1992) estimated from this theory the mass loss rate for an A2 dwarf to be about $10^{-12.5} M_{\odot} \mathrm{yr}^{-1}$.

On the other hand, Willson *et al.* (1987) conjectured that the A and F main-sequence stars in the pulsation instability strip lose mass at rates in the range 10^{-9} to $10^{-8} M_{\odot} \mathrm{yr}^{-1}$, which would have a significant evolutionary effect during their main-sequence lifetime. Such A stars would evolve down the main sequence towards G dwarfs. It would resolve problems like the discrepancy

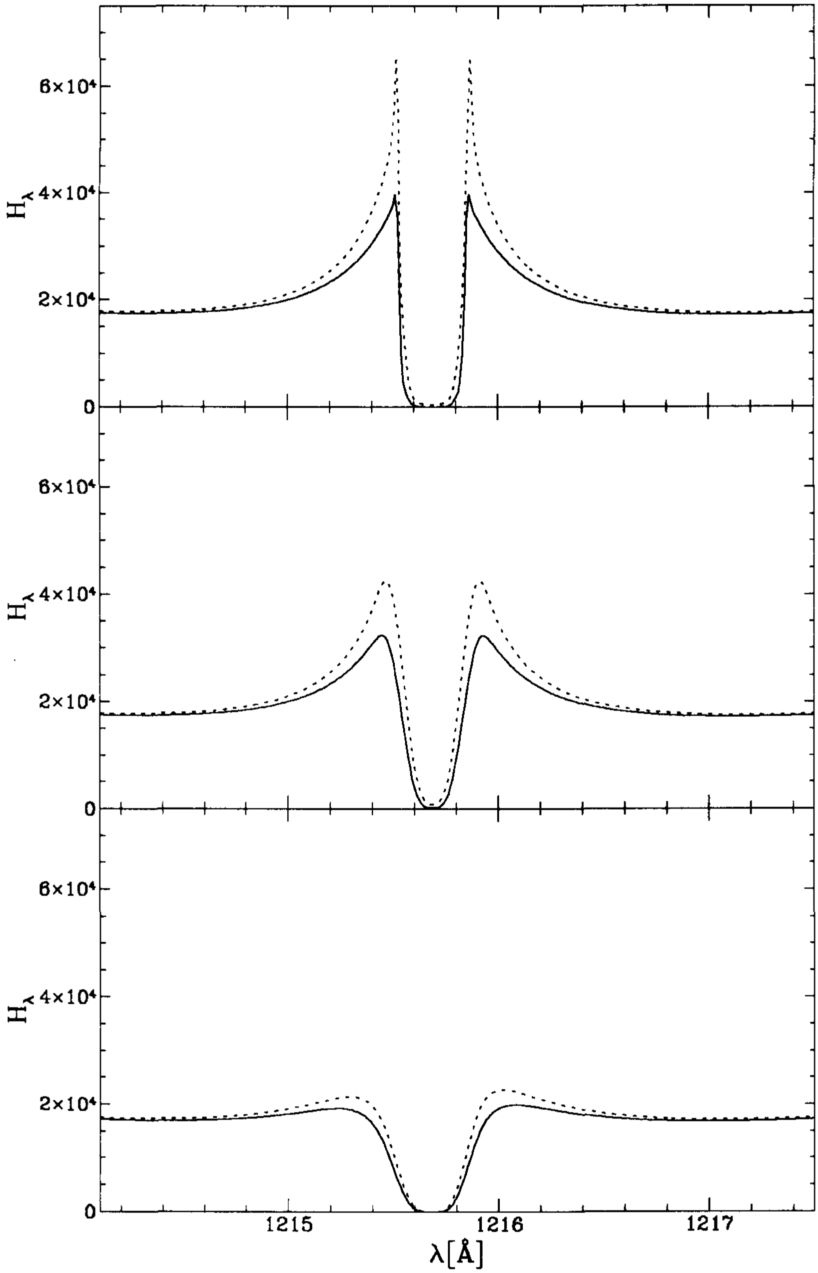

Fig. 3. Comparison of the Lyman α line cores for the two models displayed in Fig. 1. Upper panel: net stellar spectrum; middle panel: the convolved spectrum as in Fig. 2; the lower panel includes the contribution of interstellar absorption (see text).

between the age of the galaxy and the age of globular clusters, the blue straggler phenomenon, and it would have implications for the derived initial mass function and the chemical evolution of the galaxy.

An undisputable determination of the mass loss in main-sequence A stars is therefore essential for a wide range of astrophysical problems. While one major achievement of *IUE* was to evidence strong mass loss in hot stars, the recorded spectra yet show a limited accuracy (S/N $\approx$ 10–20) implying that the lowest mass loss rates detectable in A stars are of the order of 10^{-9} to $10^{-8} M_{\odot} \mathrm{yr}^{-1}$. These limits are similar to the rates conjectured by Willson *et al.* (1987) and it would be difficult to assess their suggestion, not to speak about the winds invoked in conjunction with radiative diffusion which are 10^4 to 10^6 times weaker! The main indicator of mass loss in the ultraviolet spectrum of A stars is the asymmetric P-Cygni type line profile of the Mg II h and k resonance lines; the blue emission becomes weaker when the particle density in the wind decreases. Good spectral diagnoses will be strong resonance lines of abundant metals, but most of them are in the ultraviolet range and no improvements might be foreseen. Therefore the ultimate choice may be the hydrogen Lyman α line. The wind composition is indeed mostly hydrogen, the metals being about more than 10^4 less abundant. We can then expect that an asymmetry in the Lyman lines would show up at a given spectrophotometric accuracy for smaller mass loss rates. Moreover we could also contemplate using the Balmer lines; whereas the population gain relative to abundant metals is lost here, we can achieve a much higher signal-to-noise ratios around Hα than in the ultraviolet region.

Besides the spectral line asymmetries, two other diagnoses of mass loss in A stars have been suggested, which may be more appropriate provided we have an independent estimate of the ionization state of the wind. A search for asymmetries in absorption line profiles of neutral or singly-ionized species offers the best hope for a detection of a cool wind. If the wind is predominantly ionized, the observation of the free-free microwave continuum emission would allow to detect small mass loss rates. If the wind has coronal temperatures, X-ray flux measurements may provide even stronger constraints on the mass loss rate. Since there is so far no evidence of X-ray emissions from single A stars, and since *IUE* did not reveal any spectral signatures of mass loss in these stars, Brown *et al.* (1990) observed a sample of A and F dwarfs with the VLA to look for the free-free emission. None of the observed stars were positively detected at 6 cm, implying upper limits for the ionized mass loss rates of 10^{-9} to $10^{-10} M_{\odot} \mathrm{yr}^{-1}$. Although the ionization state of a wind from an A dwarf involves a considerable uncertainty, these results practically rule out the conjecture of Willson *et al.* (1987). On the other hand, Linsky *et al.* (1992, and these proceedings) reported that some late Bp magnetic stars are radio sources, while no flux was detected for magnetic Ap stars. They interpreted this emission as a gyrosynchrotron emission from non-thermal electrons in the stellar magnetospheres.

The Hα line profile in main-sequence A stars

Recently Lanz & Catala (1992) recorded spectra with very high signal-to-noise ratios of 5 bright main-sequence stars of the region around Hα, with the purpose to search for very weak asymmetries and to investigate to what extent the upper limits for the observed mass loss rates may be pushed down by this method. It appeared certain that the idea of Willson *et al.* (1987) can be definitely proved or disproved, but what about a direct observational support of the extremely small

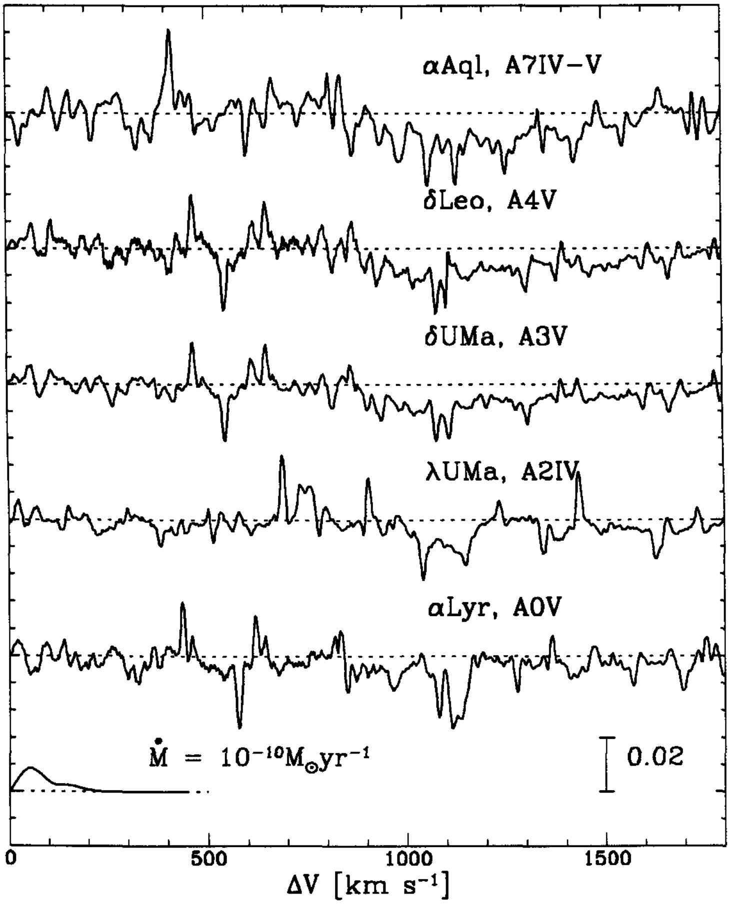

Fig. 4. Observed differences between the red and blue wings of Hα in 5 bright main-sequence A stars, and predicted asymmetry for a mass loss rate of $10^{-10} M_\odot \mathrm{yr}^{-1}$.

mass loss rates advocated by Michaud and collaborators? From several tens of individual spectra recorded for each star from Observatoire de Haute-Provence with the spectrometer Aurélie attached to the 1.52m telescope, Lanz & Catala (1992) finally acquired spectra with signal-to-noise ratios of 2000-2500. They assessed very carefully such very high spectrophotometric accuracy. At the 3σ level, asymmetries down to about $1.2\,10^{-3}$ might thus be detected.

The symmetry of the line profiles was examined by folding the red wing over the blue wing around the line center. While no asymmetries showed up, the main problem is related to telluric lines, which are strong and numerous, especially in the blue wing. Lanz & Catala (1992) modeled these telluric absorptions to reduce as far as possible their hindering effect. The differences between the two wings are displayed in Fig. 4, after removing the telluric lines. No asymmetry is found in the central part of Hα up to 800 km·s^{-1}. The red wing is deeper between 1000 and 1500 km·s^{-1} for the three stars with the later spectral types due to blending with Fe I lines. Despite the very high signal-to-noise ratios, the imperfect correction for telluric absorptions limits the final accuracy. The upper limits to the asymmetry may nevertheless be set to 0.3 to 0.5 %, while it is somewhat larger for α Aql (0.7%).

In order to assess what upper limit on the mass loss rate can be inferred from these observations, Lanz & Catala (1992) calculated Hα profiles for a grid of model atmospheres of an A0V star surrounded by a weak wind. The parameter space was explored in several directions, varying the mass loss rate, the velocity law and the turbulent velocity in the wind. The Herbig Ae stars are the only non-evolved A stars for which the wind has been detected, and therefore Lanz & Catala (1992) also used them as guidelines. In particular, the terminal velocity of the wind was assumed to be 300 km·s^{-1}. Lanz & Catala (1992) found that the asymmetry decreases when the velocity gradient in the wind is located closer to the stellar photosphere, and when the turbulent velocity increases. Moreover the asymmetry is almost proportional to the mass loss rate for such weak winds. Assuming the most stringent wind model parameters to derive the most meaningful upper limits for the mass loss rates, Lanz & Catala (1992) derived the upper limits for the mass loss rates to be 1 to 2 $10^{-10} M_{\odot}\mathrm{yr}^{-1}$ for these 5 bright main-sequence A stars. In Fig. 4, the theoretical asymmetry calculated for a mass loss rate of $10^{-10} M_{\odot}\mathrm{yr}^{-1}$ illustrates well these upper limits. It is likely that repeating the observations in a very dry site could reduce these limits by a factor up to ten. Nevertheless it must be emphasized that looking for very weak asymmetries (10^{-3} or lower) is not only a problem from the observational point of view, but also from the theoretical one, since we must also know the Stark profile at this accuracy. Unfortunately, this is presently not the case; however it is clear that asymmetries in the Stark profile may well be of this order.

The upper limits derived by Lanz & Catala (1992) are similar or somewhat lower than those of Brown *et al.* (1990). Despite no detection, this is a very encouraging result since the two methods are completely independent on the observational as well as on the theoretical grounds. Combined, these two studies convincingly disprove the suggestion of Willson *et al.* (1987), but they give very little hope that the mass loss invoked in the framework of radiative diffusion models could be directly detected. The best indirect signature of such weak wind might well be the chemical peculiarities and their distribution over the stellar surface.

FUTURE OUTLOOKS

At the time this brief review is written, there is no direct observational evidence for chromospheres nor for winds in main-sequence A stars. Progresses in modeling these stars nevertheless suggest that the Lyman α and the Mg II h and k line cores are potentially good indicators of the physical conditions in the uppermost layers, if a sufficient spectrophotometric accuracy can be achieved and if the interstellar absorption can be modeled. Such an accuracy may in principle be reached with the *HST*. On the other hand, *ROSAT* opens new possibilities to detect X-ray emissions from A stars and its all-sky survey will provide an opportunity to re-assess the question of coronae in A stars. However, it may turn out that in most cases the X-ray emission comes from hot white dwarf companions, such as the system of β Crt discovered by Fleming *et al.* (1991). The study of the outer layers in A-type stars deserves a renewed observational effort in regard to the present opportunities, because it may significantly contribute to our understanding of these atmospheres and their peculiarities.

Acknowledgement: The work on this project was supported in part by the NASA grant No. 65 under program NRA 91–OSSA–12.

REFERENCES

Babel J., 1992, A&A 258, 449.

Blanco C., Bruca L., Catalano S., Marilli E., 1982, A&A 115, 280.

Böhm-Vitense E., Dettmann T., 1980, ApJ 236, 560.

Brown A., Vealé A., Judge P., Bookbinder J.A., Hubeny I., 1990, ApJ 361, 220.

Bruhweiler F.C., Vidal-Madjar A., 1987, in *Exploring the Universe with the IUE Satellite*, eds. Kondo Y. *et al.* , Reidel, Dordrecht, p. 467.

Cassinelli J.P., Lamers H.J.G.L.M., 1987, in *Exploring the Universe with the IUE Satellite*, eds. Kondo Y. *et al.* , Reidel, Dordrecht, p. 139.

Conti P.S., Underhill A.B., 1988, *O Stars and Wolf-Rayet Stars*, Mon. Ser. on Nonthermal Phenomena in Stellar Atmospheres, NASA-SP 497.

Crivellari L., Praderie F., 1982, A&A 107, 75.

Dravins D., 1981, A&A 96, 64.

Fleming T.A., Schmitt J.H.M.M., Barstow M.A., Mittaz J.P.D., 1991, A&A 246, L47.

Freire-Ferrero R., 1979, A&A 78, 148.

Freire-Ferrero R., 1986, A&A 159, 209.

Freire-Ferrero R., Czarny J., Felenbok P., Praderie F., 1977, A&A 61, 785.

Freire-Ferrero R., Czarny J., Felenbok P., Praderie F., 1978, A&A 68, 89.

Freire-Ferrero R., Gouttebroze P., Kondo Y., 1983, A&A 121, 59.

Freire-Ferrero R., Gouttebroze P., Talavera A., 1987, A&A 173, 315.

Holweger H., 1992, in *The Atmospheres of Early-Type Stars*, Eds. Heber U., Jeffery C.S., Lecture Notes in Phys. 401, Springer-Verlag, Berlin, p. 48.

Hubeny I., Stefl S., Harmanec P., 1985, Bull. Astron. Inst. Czechosl. 36, 214.

Golub L., Harnden F.R., Maxson C.W., Rosner R., Vaiana G.S., Cash W., Snow T.P., 1983, ApJ 271, 264.

Lanz T., Catala C., 1992, A&A 257, 663.

Linsky J.L., Drake S.A., Bastian T.S., 1992, ApJ 393, 341.

Michaud G., Charland Y., 1986, ApJ 311, 326.

Michaud G., Dupuis J., Fontaine G., Montmerle T., 1987, ApJ 322, 302.

Pallavicini R., Golub L., Rosner R., Vaiana G.S., Ayres T.R., Linsky J.L., 1981, ApJ 248, 279.

Praderie F., 1981, A&A 98, 92.

Schmitt J.H.M.M., Golub L., Harnden F.R., Maxson C.W., Rosner R., Vaiana G.S., 1985, ApJ 290, 307.

Seggewiss W., 1990, A&A 229, 186.

Shore S.N., Brown D.N., Sonneborn G., 1987, AJ 94, 737

Willson L.A., Bowen G.H., Struck-Marcell C., 1987, Comments Ap. 12, 17.