# NEW INSIGHT INTO THE PHYSICS OF ATMOSPHERES OF EARLY TYPE STARS

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ABSTRACT

The insight into the physics of atmospheres of early type stars obtained from IUE observations is discussed. The paper is concentrated on the phenomenon of mass loss and stellar winds from hot stars, since many of the IUE observations of early type stars were directed to that problem. The mass loss rate of early type stars increases by about a factor of $10^2$ to $10^3$ during their evolution. This seems incompatible with the radiation-driven wind models and may require another explanation for the mass loss from early type stars. The winds of early type stars are strongly variable and the stars may go through active phases. Eclipses in binary systems by the stellar winds can be used to probe the winds. A few highly interesting future IUE studies are suggested.

## I. INTRODUCTION

Ultraviolet astronomy has changed our ideas about early type stars (O,B,A) rather drastically. About fifteen years ago there was a general tendency to believe that the atmospheres of these stars were reasonably well understood. Although there were still quantitative discrepancies between observed and predicted spectral features, the physical processes in the atmospheres were considered to be well known. In a way, the atmospheres of hot stars were very simple: a they were in hydrostatic equilibrium, b and in radiative equilibrium, convection not being important c the opacities are mainly due to simple atoms.

Although these physical assumptions were simple, the actual calculation of stellar atmospheres was still difficult, because of two complicating factors: firstly, the large radiative intensities and the small particle densities made it necessary to consider deviations from thermodynamic equilibrium (non-LTE) in the calculation of the continuum and line opacities. And secondly, the effect of line-blanketing in the ultraviolet could change the temperature stratification of the atmospheres by back-warming. At about that time Mihalas and colleagues started the calculation of non-LTE models, while Morton and co-workers calculated the first line-blanketed model atmospheres for hot stars. It would be just a matter of time and bigger computers to bring the theory and observations into agreement.

There were a few stars (and very few astronomers) that did not fit this general scheme: e.g. the Wolf-Rayet stars with their strong emission lines and large outflow velocities; the star P Cygni with its characteristic line profiles (P Cygni profiles) indicating mass ejection; the shell stars with their narrow shortward shifted absorption lines; the magnetic Ap-stars and the metallic Am-stars with their peculiar abundances. It was obvious that for these stars additional physical processes had to be taken into account, such as mass-ejection or magnetic fields. However, as these kinds of stars were rather extreme, their existence did not shake the general belief that the atmospheres of early type stars are in principle very simple and not very exciting.

The physical reason for this was, of course, the fact that the visual spectrum only shows us the tail of the energy distribution curves for the early type stars. Since the radiation in this tail is not very sensitive to the physical processes in the atmospheres, most of the interesting properties of early type stars remained hidden for the ground-based astronomers by the Earth's atmosphere. It is in this respect not surprising that UV astronomy in general and the Copernicus and IUE observations in particular have changed our insight into the structure and evolution of early type stars.

In this paper I will concentrate on the new knowledge obtained by IUE, extending the many interesting results obtained by the Copernicus satellite, on the structure and stability of early type stellar atmospheres.

## II. MASS LOSS IN THE HR-DIAGRAM

The first high-resolution UV observations of Morton and his colleagues (e.g. Morton, 1967) showed that early type supergiants are ejecting mass with a velocity of about 2000 km/s at a rate of about $10^{-6}$ $M_{\odot}$/yr. The Copernicus satellite has extended these observations to a large number of stars (Snow and Morton, 1976; Lamers and Snow, 1978), indicating that all early type stars with $M_{bol} < -6$ ($L > 2\ 10^4\ L_{\odot}$) are losing mass at a rate high enough to be observable ($\dot{M} > 10^{-9} - 10^{-10}$ $M_{\odot}$/yr). Stars with lower luminosity only lose mass if their rotational velocity is large enough (v sin i > 200 km/s) (Snow and Marlborough, 1976; Lamers and Snow, 1978).

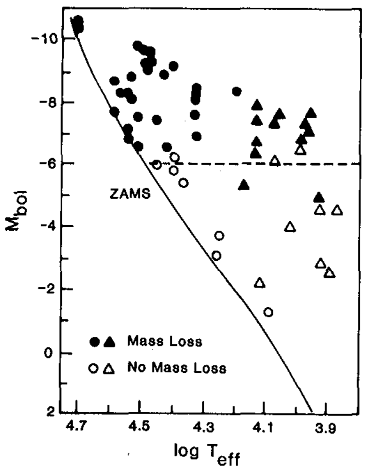


Figure 1

The distribution of stars with and without observable mass loss in the HR diagram. Circles: Snow and Morton (1976) Copernicus; Triangles: Lamers et al. (1980a); IUE.

The Copernicus observations left a gap in the hot part of the HR diagram unobserved; the region of $T_{eff}$ < 20 000 K and $M_{bol}$ > -6 occupied by stars of types B3 and later, and luminosity classes III, II and Ib. Lamers et al. (1980a) have filled in this gap with IUE observations of 22 stars of spectral types B5 to F0. The search for mass loss indicators in the UV resonance lines (P Cygni profiles or extended violet absorption wings) is summarized in Figure 1. This figure shows that the limit of observable mass loss occurs at $M_{bol} \simeq -6$ over the entire range of $7500 < T_{eff} < 40\,000$ K. If we remember that the evolutionary tracks of massive stars are approximately horizontal in the HR diagram, this implies that stars which do not lose mass at the main sequence ($M_{bol} > -6$) will not lose mass in the hydrogen shell-burning phase either. Stars which do suffer mass loss on the main sequence will continue to do so in the hydrogen shell-burning phase.

The fate of rapidly rotating stars of $M_{bol} > -6$ at the main sequence is still uncertain. They may lose mass during the hydrogen core burning, but when the star expands with conservation of angular momentum in each layer, the rotation-induced mass loss may stop. IUE observations of slightly evolved B-stars are required to answer this question.

Apart from the region in the HR diagram shown in Figure 1, mass loss also occurs in very hot highly evolved stars like some O-subdwarfs and central stars of planetary nebulae. These will be discussed by Heap (these proceedings).

## III. MASS LOSS RATES

The most extended set of mass loss rates for early type stars prior to IUE was from Barlow and Cohen (1977) based on the infrared excess of 44 luminous O, B and A stars, ranging in temperature from 8500 to 50000 K. The rates derived by these authors show a correlation with luminosity: $\dot{M} \propto L^{1.15}$. These observations provided a very strong argument in favor of the radiation-driven wind theory from Castor et al. (1975) which predicted $\dot{M} \propto L^{1/\alpha}$ with $\alpha \simeq 0.80$ and a very weak dependence on gravity. However, the stars studied by Barlow and Cohen were only supergiants and there was some indication that at least one main sequence star ($\tau$ Sco, B0 V) had a much smaller rate.

Recent IUE observations of main sequence O-stars have changed this picture drastically. A combination of the mass loss rates from evolved O and Of stars (Lamers et al., 1980b) with those of unevolved O V stars (Conti and Garmany, 1980) shows very clearly that the mass loss rate is not a simple function of luminosity, but that it increases drastically from O V, through O III or O(f) to O f stars (Figure 2). The rates for O (f) and O f stars are about a factor 30 and 100 respectively, larger than those for O V stars of the same luminosity. The rates for WR-star of the same luminosity are about a factor 10 larger than for the O f stars. Remembering that the evolutionary tracks are approximately horizontal in the HR diagram, we can express this behavior in terms of evolution. The stars with initial mass $M > 15\ M_\odot$ ($M_{bol} < -6$) have a small mass loss rate near the main sequence. The mass loss rate increases very strongly by about a factor 100 during the hydrogen core-burning phase to the hydrogen shell-burning phase. The Wolf-Rayet stars, which supposedly represent an even later stage of evolution, (Conti, 1976) have again higher rates. So the mass loss rate increases during the stellar evolution by as much as a factor $10^2$ or $10^3$, whereas the luminosity hardly changes.

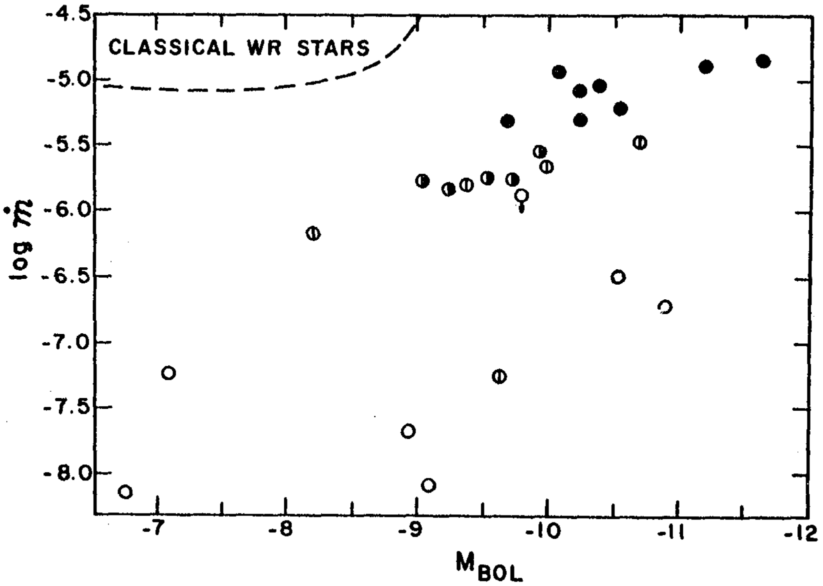


Figure 2

Mass loss rates from O-stars. Notice the large range of $\dot{M}$ for constant luminosity (Conti and Garmany, 1980).

Obviously, the luminosity is not the main parameter which determines the mass loss rate, contrary to the predictions of the radiation-driven models. This suggests very strongly that we may have to look for an alternative mass loss mechanism which should be closely connected to the evolution stage of the star and thus its interior structure.

## IV. THE ACCELERATION OF THE STELLAR WIND

Whatever the mechanism may be that determines the mass loss rate from a star, the large outflow velocities which have been observed in the UV resonance lines are most likely due to radiative acceleration (e.g. Cassinelli et al., 1978). One way to determine the acceleration is to measure the terminal velocity, $v_\infty$, reached in the wind at a large distance from the star. (This should not be confused, as is often done, with the edge velocity, $v_{edge}$, measured from the extension of the violet wings of the UV resonance lines: for stars with a small mass loss rate $v_{edge}$ can be much smaller than $v_\infty$).

The most extensive study of terminal velocities, prior to IUE, was made by Abbott (1978), who found $v_\infty \simeq 3 \times v_{escape}$. This agreed very well with the radiation-driven wind models, which predict $v_\infty = (\alpha/1-\alpha)^{1/2} v_{escape}$ if $\alpha \simeq 0.90$. The IUE observations of late-B and -A type supergiants show that the ratio $v_\infty/v_{esc}$ decreases towards the cooler stars, and reaches a value of about 0.5 for A type supergiants (Lamers et al., 1980a, Figure 3). This indicates that the radiation pressure is much smaller in the winds of A-stars than in O-stars, as might have been expected. In this respect it is interesting to notice that the mass loss rates of A-supergiants are also much less than those of O-stars of the same luminosity (Praderie et al., 1980).

Radiation pressure may not be the only mechanism which accelerates stellar winds, as it may be insufficient to explain the large velocities of the WR stars. For example, Willis et al. (1979) derived a mass loss rate of $1.1 \times 10^{-4}$ $M_{\odot}$/yr and $v_{\infty}$ = 1600 km/s for the WR star $\gamma$ Velorum

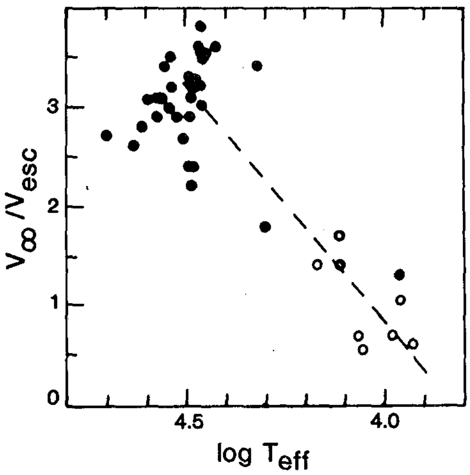


Figure 3
The ratio between the terminal velocity and the escape velocity decreases with decreasing effective temperature. Dots: Abbott (1978), Circles: Lamers et al. (1980a).

(WC8 + O9I) from IUE observations. The momentum of the wind is $\dot{M}v_{\infty}$ = $1.1 \times 10^{30}$ erg/cm s. The total momentum of the radiation is L/c = $1.3 \times 10^{28}$ erg/cm s. So the momentum of the wind is about 90 times as large as the momentum of the radiation. Unless each photon can be scattered a large number of times in opposite parts of the stellar winds (bouncing back and forward between the front and rear end of the wind) the radiation pressure is largely insufficient to explain the large wind velocity.

This suggests that not only do we have to look for another mass loss mechanism for hot stars (see III), but also for an additional mechanism to accelerate the winds, at least in WR stars.

## V. THE HEATING OF STELLAR ENVELOPES

The Copernicus observations have shown that the stellar winds are superionized, i.e. the degree of ionization is higher than can be accounted for by a wind in radiative equilibrium with the photospheric flux. In particular Snow and Morton (1976) and Lamers and Snow (1978) have shown that there is a one-to-one correlation between superionization and mass loss (including the Be-stars), suggesting that the two phenomena are in some way connected to each other. The origin of this superionization is unknown, but its presence indicates that somewhere above the photosphere, the stellar gas is heated considerably. The heating may occur in the subsonic part of the envelope, giving rise to a thin hot corona ($\Delta R \simeq 0.1\ R_{*}$, $T \simeq 5 \times 10^{6}$; Cassinelli et al., 1978); in the trans-sonic region of the wind (Cannon and Thomas, 1977); or in the extended supersonic part of the wind, producing either a homogeneous warm wind ($T \simeq 2 \times 10^{5}$ K; Lamers and Morton, 1976) or an inhomogeneous wind with hot bow shocks of high density and high velocity blobs ($T \simeq 10^{6}$ K; Lucy and White, 1980).

The recent observations of x-ray fluxes from hot stars by the Einstein Observatory (Long and White, 1980) suggests that the temperature should be in the range of $10^6$ - $10^7$ K and that the hot region is not located deep in the wind, as predicted by the thin coronal model.

The IUE observations have given two very interesting results in this respect. Firstly, Underhill (1980) found two narrow emission peaks in the spectrum of the A0 supergiant HR 1040 at the wavelength of the two C IV

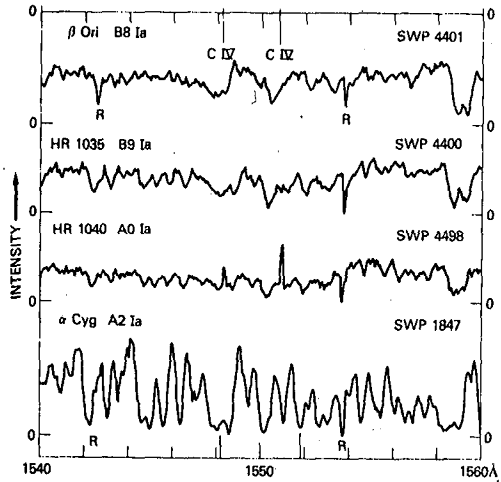


Figure 4

The C IV resonance lines (λ 1548.19, 1550.76) in the IUE spectra of four supergiants. Notice the C IV emission peaks in the spectrum of HR 1040 (A0 Ia) (Underhill, 1980).

lines. These were not found in the IUE spectrum of the same star observed by Praderie et al. (1980). If the two peaks are real (and not due to particle noise) their presence indicates the existence of a variable chromospheric activity in the winds of supergiants of types as late as A0.

Secondly, the IUE observations of the two extreme supergiants P Cyg (B1 Ia) and $\zeta^1$Sco(B1 Ia - 0) which have a mass loss rate of about $2 \times 10^{-5}$ $M_\odot$/yr show the presence of narrow absorption features or P Cygni profiles of low ions (Fe II, Al II, Mg II) in the wind (Hutchings, 1979; Cassatella et al., 1979; Wolf and Appenzeller, 1979). Although the winds of early type supergiants are generally superionized, the winds of extreme supergiants with very large mass loss rates have a low degree of ionization. This behavior might be explained by assuming that the dissipation of nonthermal energy in the stellar envelopes is not sufficient to heat the very dense winds of extreme supergiants because of the high radiative cooling rate. This situation resembles the presence of low ionization stages such as Fe II in the spectra of early type shell stars.

## VI. VARIABLE STELLAR WINDS

The envelopes of early type stars are variable on timescales of hours-to-years. The best tracer of variability in the visual spectrum is the $H_\alpha$ line and variations in the $H_\alpha$ profiles have been reported for various kinds of early type stars, such as supergiants and Be-stars (Snow et al., 1980; Stalio et al., 1979; Doazan et al., 1980). Apart from the

Be-stars the changes in the profiles are usually not very drastic, but the timescale of about one hour is surprisingly short. The UV resonance line profiles observed by Copernicus and BUSS also showed large variations on timescales of hours-to-months (York et al., 1977; Snow et al., 1980; Lamers et al., 1978). On the basis of these observations I proposed that mass loss is not a stationary process in early type stars, but that it occurs in "puffs": sudden ejections of gas from the star (not necessarily spherically symmetric) which are accelerated by radiation pressure. A similar process may occur in variable Be-stars during their active phases, in which case the puffs might be spherically or rotationally symmetric.

The IUE observations have provided a few very interesting examples which demonstrate how strong the variations can be. Heck et al. (1980) have identified six components in a number of UV resonance lines in $\zeta^1$Sco on June 21, 1979, which they attribute to the occurrence of a large number of puffs. On September 13, 1979, most of the components had disappeared.

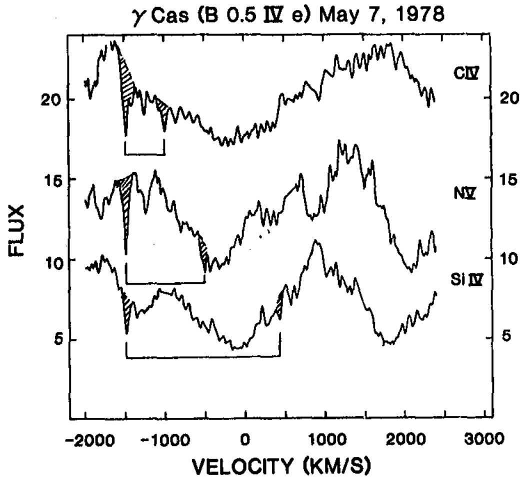


Figure 5

The UV resonance lines of C IV, N V and Si IV in the IUE spectrum of γ Cas (B0.1 IV e). Notice the narrow absorption components at -1500 km/s (Henrichs et al., 1980).

It is interesting to note that the time of highest puff-activity coincides with a sharp drop in visual brightness of about 0.15 magnitude.

A different, but possibly correlated, type of variation has been observed in the IUE spectrum of γ Cas (B0.5 IVe). In six out of ten IUE spectra obtained from this star the lines of N V, C IV and Si IV have sharp absorption components at about -1500 km/s (Doazan et al., 1980; Henrichs et al., 1980, Figure 5). The appearance and disappearance of these components suggest that puffs or shells are ejected very frequently from this star. Because of their large outflow velocities (possibly due to radiative acceleration) the narrow components can only be observed for about one week. (For an alternative explanation see Thomas et al., these proceedings.)

These kind of observations show that mass loss may be a highly nonstationary phenomenon in early type stars and that at least several kinds of stars go through active phases. This again suggests that mass loss cannot be due to radiation pressure only.

## VII. PROBING THE STELLAR WINDS IN BINARIES

A few late type giants and supergiants, such as $\zeta$ Aur, have an early type comparison which can be used to probe the envelope of the late type star, by studying the spectrum of the B-star when it moves behind the extended envelope. The same approach can be used for the study of a few early type binary systems.

Willis et al. (1979) has obtained IUE spectra of the Wolf-Rayet binary $\gamma$ Velorum (WC8 + 09I) in six different phases of the binary period. Although this system is not an eclipsing binary in the visual spectrum, the winds of both stars are so extended that eclipse effects can be seen in many UV lines. As an example we show in Figure 6 the ratio of two IUE spectra at $1500 \lesssim \lambda \lesssim 1900$ Å, between phase 0.51 (when the O-star was behind the envelope of the WR star) and phase 0.1. The many absorption features in this ratio-spectrum show the presence of the corresponding absorbing ions in the wind of the WR star. By studying the phase dependent

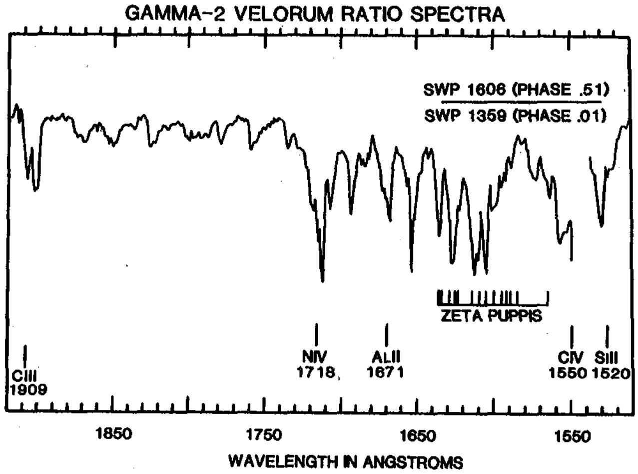


Figure 6

The ratio of two IUE spectra of the WR binary $\gamma$ Velorum (WC8 + 09 I). The absorption lines are due to eclipse of the O-star by the wind of the WR star at phase 0.51 (Willis et al., 1979).

behavior of lines of high and low excitation and ionization Willis et al. demonstrated that the wind of the WC star is highly ionized but that the degree of excitation is low ($T_{exc.} \simeq 10\ 000$K). This may be due to the same mechanism which cools the winds of the high mass loss supergiants $\zeta^1$Sco and P Cyg.

A careful study of the UV-line eclipses in a few early type binaries with a wind would be extremely useful in determining the variation of density, velocity and ionization in the stellar winds.

## VIII. EARLY TYPE STARS IN OTHER GALAXIES

The brightest early type stars in the LMC and SMC can be observed with IUE. Since the metal abundance in both galaxies is smaller than in our galaxy, a differential study of stars in the LMC/SMC compared to galactic stars of the same temperature and luminosity will demonstrate the effect of metal abundances on stellar winds. The radiation pressure forces which presumably accelerate the winds of luminous OB stars are largely due to line opacities of CNO ions (Lamers and Morton, 1976). If the mass loss were due to radiation pressure, stars with smaller CNO abundances are expected to have smaller mass loss rates. If the mass loss is due to some other mechanism (see III) and the radiation pressure only acts in accelerating the wind, we might expect that the mass loss rates are the same in LMC/SMC stars and galactic stars, but that the wind velocities of the SMC/LMC stars are smaller than those of similar galactic stars.

Hutchings (1980) has studied the IUE low resolution spectra of 7 LMC supergiants and he found evidence that the radial velocities at minimum intensity in the lines are about 0.7 times as large as those in corresponding galactic stars. This, however, does not necessarily imply that the wind velocities in the LMC stars are smaller. The theoretical P Cygni profiles calculated by Castor and Lamers (1979) showed that a decrease in line opacity (e.g. due to a smaller abundance of the observed ion) will reduce the velocity at the line minimum, even if the wind velocity does not change at all. Nevertheless, these first IUE observations of the LMC/SMC stars are interesting since they demonstrate that differences with galactic stars do exist. A careful study of the UV lines combined with a study of $H_\alpha$ to estimate the mass loss rates independently, might turn out to be very valuable for our understanding of the mass loss phenomenon.

## IX. CONCLUSIONS

I have concentrated on the subject of mass loss and stellar winds from early type stars. There are two reasons for this: firstly, I think that this is the most important problem in the study of early type stars as it may change our concepts on the structure of stellar atmospheres and evolution of massive stars, and secondly, this is a subject to which many IUE studies were directed and where IUE observations have made a very important contribution.

Let me summarize the new insights which we have gained from the IUE observations:

a The mass loss rate of an early type star with $L > 2 \times 10^4 L_\odot$ increases drastically during its evolution. It may increase by about a factor 30 from the zero age main sequence to the hydrogen shell burning phase, and another factor of 10 when it becomes a WR star. This rapid increase seems to be incompatible with the radiation-driven wind theory and may require another mass loss mechanism which should be closely related to the stellar evolution phase.

b The terminal velocities in late-B and -A supergiants are considerably smaller than those of O-stars, indicating a less efficient acceleration mechanism. The momentum of the stellar winds of WR stars is about $10^2$ times larger than the momentum of the radiation. This suggests that, at least in WR stars, the acceleration is produced by a mechanism much more efficient than radiation pressure.

c The presence of hot gas in the stellar winds as first suggested by the UV lines from high ionization stages such as N V and O VI, is confirmed by the observed x-ray fluxes. The winds of the extreme B-supergiants with $\dot{M} \simeq 2 \times 10^5$ $M_\odot$/yr and the dense shells of shell stars, however, have low ionization and excitation temperatures.

d The winds of early type stars are variable on a time scale of hours-to-years. The observations of a few early supergiants and of Be-stars show that stars may go through active phases in which puffs or shells are ejected frequently. For one star, $\zeta^1$Sco, the active phase was found to coincide with a decrease in visual magnitude.

The examples which I have given are in a way extremes in terms of variability or mass loss. It is possible that we can explain the physics of the more normal mass losing stars by ignoring these extremes. I am afraid, however, that this is not very likely.

P.S. Based on our present knowledge, I can suggest a few IUE studies which would be most valuable in providing insight into the physics of mass loss from hot stars: 1: the study of few binary systems in which the wind can be probed by eclipses in the UV lines; 2: the study of the variability of a few stars in detail in UV, visual and x-rays; 3: the study of mass loss and wind velocities of similar stars (same L and $T_{eff}$) with different abundances.

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