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MASS LOSS FROM HOT STARS

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RESUMEN

Se presenta un resumen de los problemas actuales de la física de pérdida de masa en estrellas tempranas. Se consideran los casos especiales de estrellas tipo OB y Be, así como las estrellas centrales de las nebulosas planetarias. Se derivan tasas de pérdida de masa para estos objetos.

ABSTRACT

Current problems in our understanding of the mechanisms of mass-loss from early-type stars are reviewed. The special cases of OB and Be stars, as well as central stars of planetary nebulae are considered and mass-loss rates are derived for these objects.

Keys words: **STARS-MASS LOSS – STARS-EARLY TYPE**

I. INTRODUCTION

Several authors have recently reviewed the theories and the diagnosis of mass-loss from early-type stars (see, for instance, Conti 1978; Cassinelli 1979; Castor 1979). Therefore, in this short presentation, I will discuss some specific points which in my opinion are relevant for stellar wind studies.

The presence of an expanding envelope is detected, in general, through the existence of P-Cygni profiles in the star spectrum. In the optical region, a large number of Of and OB supergiants present H-Balmer emission lines with violet-shifted absorption features and in some high-luminosity stars, the He II λ 4686 recombination line is also present in emission (Conti and Leep 1974). In the ultraviolet region, those stars having gas flowing supersonically toward the observer also display P-Cygni profiles in the resonance and subordinate lines of highly ionized atoms, in which, the blue absorption edges indicate outflow velocities in the range of 1000 to 3000 km s^{-1}.

The interpretation of P-Cygni profiles can give some direct information on the velocity profile V(r) throughout the envelope and on the rate of mass loss from the star. However, such analysis is difficult for the following reasons: the lines observed in the optical region are generally formed by a combination of emission and scattering, corresponding to transitions between excited states whose populations are very uncertain. On the other hand, the UV resonance lines are pure scattering lines by ions in their ground level, but our knowledge of the ionization state in the envelope is still far from being understood.

The presence of highly ionized species like O V, N V, C IV in a large extension of the envelope can be explained by radiative ionization from the photospheric emission if the brightness temperature in the He II continuum is about 4×10^4 °K, or by collisional ionization if the electron temperature is of the order of 2×10^5 °K. This last possibility defines the "warm" wind model proposed by Lamers and Rogerson (1978) and Lamers and Snow (1978).

Cassinelli, Olson and Stalio (1978) proposed a model in which the O VI and N V lines in O stars and the C IV lines in B supergiants may be due to Auger ionizations by soft X-rays from a thin hot corona existing at the base of a "cool" envelope. Very recently, the *Einstein* satellite experiment has found that most of the O stars are weak X-ray sources with a luminosity of the order of 10^{-5} times the bolometric emission of the star. These observations give more support to the idea that soft X-rays from an inner hot corona are responsible for the presence of these highly ionized species in the expanding envelope. Cassinelli and Olson (1979) determined the parameters of the corona in order to reproduce the ionization conditions in ζ Pup and they found that a volume emission measure of 2.5×10^{58} cm^{-3} and a coronal temperature of 5×10^6 °K can explain the required ionization structure in a "cold" wind having a temperature of about 3×10^4 °K. These coronal conditions imply a ratio between the X-ray to the photospheric luminosity of about 5×10^{-5}, consistent with the *Einstein* results.

II. MASS-LOSS FROM OB STARS

Although some hints to determine the ionization structure are now appearing, two stars (ζ Pup and τ Sco) that have a well studied UV spectra gave conflicting results: Lamers and Morton (1976) found that the ionization balance in ζ Pup does not vary with radius in the envelope while in τ Sco the degree of ionization

TABLE 1

BASIC DATA FOR SOME ILLUSTRATIVE OB STARS

Star	HD	M_b	R ($R_\odot$)	T_* (°K)	V_∞ (km s^{-1})	Sp	D (kpc)
9 Sgr	164794	−10.5	15	50000	3440	O4((f))	1.6
ζ Pup	66811	−10.0	17	42660	2660	O4 ef	0.45
–	153919	− 9.2	17	35000	2470	O6 f	1.7
ζ Ori	37742	− 9.2	24	29000	2290	O9.5I	0.46
ε Ori	37128	− 9.7	33	28840	2010	B0Ia	0.44
–	152667	− 9.5	38	25000	1640	B0I	2.16

decreases with distance (Lamers and Rogerson 1978). The star P-Cygni is another example of contradictory conclusions obtained from the analysis of the data. Barlow and Cohen (1977), from the infrared and radio observations, found a very slow acceleration for the wind. Van Blerkom (1978) showed that the Balmer profiles can be explained by a "linear" velocity law while Kuan and Kuhi (1975) derived a decelerating flow in the envelope. All of these examples demonstrate how crucial the knowledge of the physical conditions in the envelope (such as the ionization structure and the excited level populations density) as well as the gas velocity profile are if we want to obtain some information from the analysis of line profiles.

A possibility to avoid these difficulties would be to estimate the rate of mass-loss from the continuum observations. Infrared fluxes of OB stars have been measured by Barlow and Cohen (1977) and radio-emission from early-type stars have been reported by Braes *et al.* (1972), Wendker *et al.* (1975), Morton and Wright (1979), Abbott *et al.* (1980) among others. At these frequencies, the continuum absorption is so strong that the apparent surface of the star is actually in the wind and the radius of this surface depends not only on the rate of mass loss but also on the density profile.

Table 1 shows the basic data for some OB stars chosen to illustrate the results that will be discussed below.

Since the velocity profile is not known *a priori*, we will adopt in what follows a velocity law of the form

$$V^2(r) = V_0^2 + V_\infty^2 (I - \frac{R}{r})\, m \quad , \qquad (1)$$

where V_∞ is the terminal wind velocity, R is the photospheric radius, V_0 is generally taken equal to the sound velocity and m is a free parameter. For instance, m = 1, simulates the velocity law obtained by Castor, Abbott and Klein (1975) for a radiation-driven wind; and the case m = 0, in which a constant velocity throughout the envelope results, was studied by Wright and Barlow (1975).

In order to compute the flux from the envelope, we will further assume that the electron temperature is constant throughout the wind. Chiuderi and Ciamponi (1977, 1978) have analysed envelopes with a polytropic equation of state and they have concluded that the estimate of the mass-loss rate in this case is not sensitive to the electron temperature at the base of the envelope.

Under these conditions, the observed flux is given by

$$f_\nu = \frac{\pi R^2}{D^2} S_\nu (T_e)\, \rho\, (m, \tau_\nu), \qquad (2)$$

where D is the distance to the star, $S_\nu(T_e)$ is the source function and the function $\rho(m, \tau_\nu)$ can be interpreted as being a numerical factor by which the stellar disk increases (at a given frequency) due to the wind effect.

From the numerical calculations by Pacheco (1980), the relation between the "effective" radius and the optical depth can be fitted by an equation of the form (valid for $\log \rho \gtrsim 1.37$).

$$\log \rho = A \log \tau_\nu + B \quad , \qquad (3)$$

where the constants A and B, as a function of the parameter m are shown in Table 2.

The effective optical depth of the wind is defined by the equation:

$$\tau_\nu = \frac{0.42}{\nu^{2.1} T_e^{1.35} R^3} \left(\frac{\dot{M}}{4\pi m_H V_\infty}\right)^2 . \qquad (4)$$

TABLE 2

CONSTANTS A AND B AS FUNCTIONS OF m

m	A	B
0.0	0.64	0.38
0.5	0.57	0.49
1.0	0.53	0.55
1.5	0.46	0.66
2.0	0.41	0.73

From equation (2), using the observed flux at a given frequency, and from the knowledge of R, D and T_e one can calculate $\rho(m, \tau_\nu)$. From equation (3), one gets τ_ν for a given velocity profile. Using now equation (4), the mass loss rate can be estimated.

The mass-loss rates thus obtained for the stars listed in Table 1 are given in Table 3. The second column gives the frequency or wavelength, where the flux measurement was made, the third column gives the flux and columns 4 and 5 the mass-loss rate. We have assumed a velocity law defined by m = 1.

The mass-loss rate can also be estimated from he recombination lines (Klein and Castor 1978). The equivalent width of the red-side of the line (including the photospheric correction, see Figure 1) allows us to calculate the luminosity due to the recessing lobes of the envelope.

Defining the parameters

$$\xi = \frac{\dot{M}^2}{(R\,V_\infty)^3} \quad , \tag{5}$$

and

$$\lambda_i = \frac{L_i}{R^2\,V_\infty} \quad , \tag{6}$$

and from the numerical calculations made by Pacheco (1980), one can made a plot in the (ξ, λ_i) plane (see Figure 2), from which the mass-loss rate can be estimated.

The results of these calculations are also given in Table 3. From this table we see that the continuum and the recombination lines give mass-loss rate estimates within a factor of two. The adopted rate (the fifth column in Table 3) was calculated giving a higher weight to the continuum results since these do not require knowledge of the population density of the excited levels.

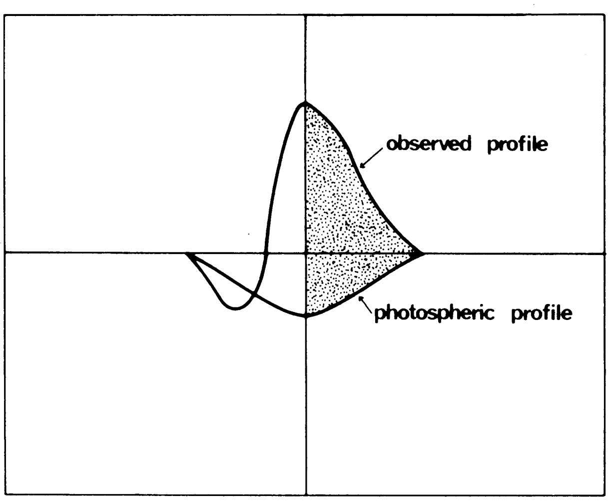


Fig. 1. Diagram that shows the contribution of the photosphere to the observed profile. The units are relative intensity versus wavelength.

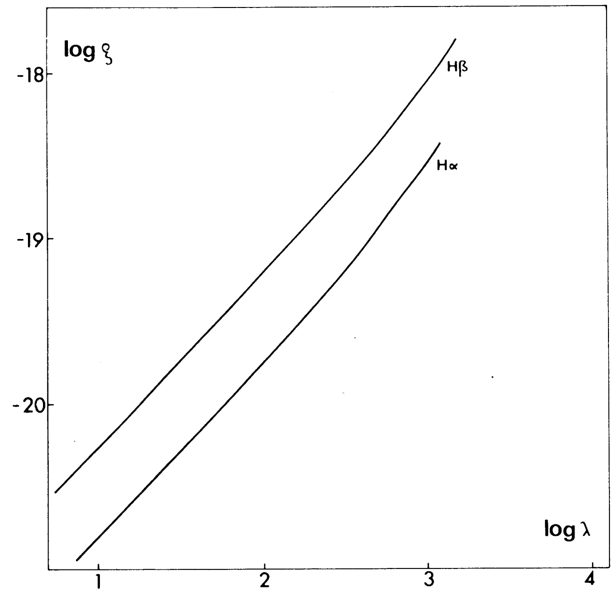


Fig. 2. Plot in the (ξ, λ) plane from which the mass-loss rate can be estimated (see details in text).

For the non-saturated P-Cygni UV lines, if we assume a velocity law with m = 1 and a constant ionization degree for the considered ion throughout the envelope, the equivalent width within the Sobolev approximation of the "blue" absorption is given by (Pacheco 1981)

$$W_\lambda \doteq 0.314 \frac{\pi e^2}{mc} f_{ij}\, \lambda_{ij}^2\, X_{ion}\, A_{el} \frac{\dot{M}}{\pi m_H c\, R V_\infty} \quad . \tag{7}$$

where f_{ij} is the oscillator strength of the line, λ_{ij} the wavelength of the transition, X_{ion} is the ionization degree of the ion, A_{el} is the abundance of the element and the other symbols have their usual meaning.

Now, if we reverse our analysis, from equation (7) using the *IUE* observations of Hutchings (1980) and Conti and Garmany (1980) and the mass-loss rates that we have already estimated, it is possible to evaluate the average ionization degree of the expanding envelope. For the stars we are considering, these averages are displayed in Figure 3. We can see that there is a slight correlation of the ionization degree with the absolute magnitude of the star in the sense of a decreasing relative fraction of Si IV and C IV ions with increasing luminosity. Although, we have not presented enough data for any

TABLE 3

MASS-LOSS RATES

Star	Spectral region	f_ν (Jy)	$\dot{M}$ (10^{-5} $M_\odot$ yr^{-1})	$\dot{M}$ (adopted) ($M_\odot$ yr^{-1})
ζ Pup	5 GHz	1.4×10^{-3}	1.1	1.3×10^{-5}
	14.7 GHz	7.2×10^{-3}	1.9	
	2.2 μ	5.6	1.5	
	Hα	1.08×10^{34}*	0.7	
ε Ori	5 GHz	1.6×10^{-3}	0.7	6.6×10^{-6}
	11.3 μ	1.16	0.6	
ζ Ori	5 GHz	7×10^{-4}	0.4	4.5×10^{-6}
	10 μ	0.5	0.4	
	Hα	0.89×10^{34}*	0.5	
9 Sgr	5 GHz	10^{-3}	11.0	1.1×10^{-4}
HD153919	Hβ	0.57×10^{34}*	0.7	7.2×10^{-6}
HD152667	3.4 μ	5.5×10^{-2}	0.6	1.0×10^{-5}
	Hβ	3.31×10^{34}*	1.7	

* For Hα and Hβ, the third column gives the luminosity in erg s^{-1} obtained from the P-Cygni profile.

definite conclusion, this may be an important clue to our understanding of the ionization mechanism or to offer the basis for a semiempirical calibration for the UV spectra.

III. MASS-LOSS FROM CENTRAL STARS OF PLANETARY NEBULAE

Recent observations with the *IUE* satellite have revealed that hot subluminous stars like the central stars of planetary nebulae present P-Cygni profiles in their spectra (Heap 1979; Benvenuti and Perinotto 1980). The blue-edge of these lines indicate flow velocities in the range of 1000 to 3000 km s^{-1} and crude mass-loss rates estimates indicate values of the order of 10^{-10} – 10^{-11} $M_\odot$ yr^{-1}.

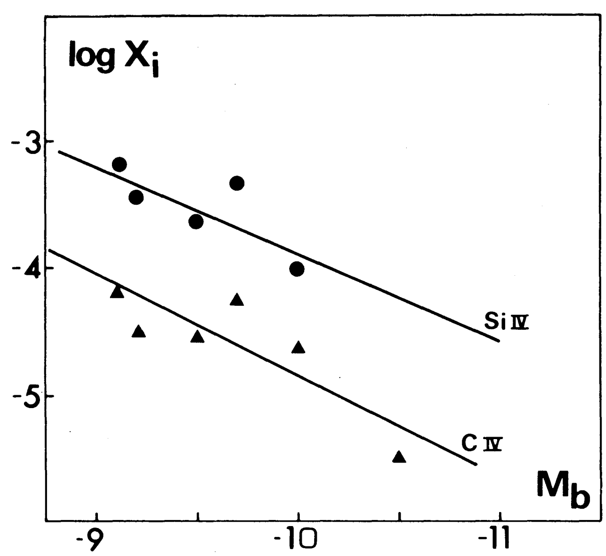


Fig. 3. Average ionization degree as a function of bolometric magnitude for the sample of stars considered in this work.

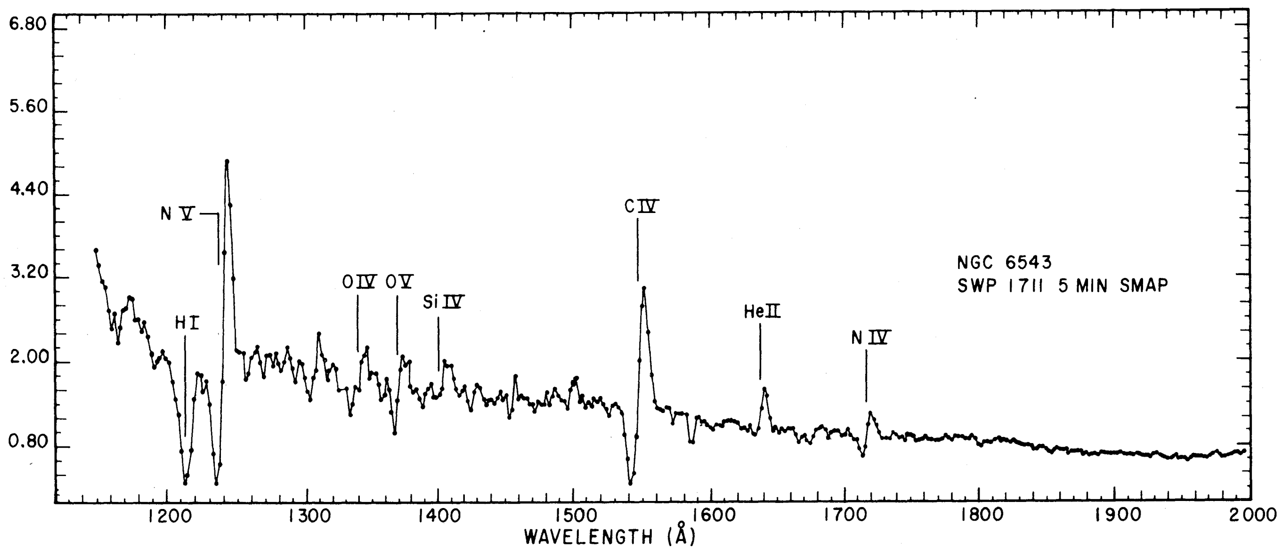
Figure 4 shows the UV spectrum of NGC 6543, in which P-Cygni profiles of the resonance transitions of N V λ1240, C IV λ1549, and Si IV λ1396 are clearly seen, as well as the subordinate transitions of O IV λ1341, O V λ1371 and N IV λ1718. This object offers an opportunity not only to evaluate the mass-loss rate but also to study the physical conditions in the wind.

Castor, Lutz and Seaton (1980) analysed the lines in the UV spectrum of NGC 6543 and they have estimated a rate of about 10^{-7} $M_\odot$ yr^{-1} for the mass loss. This was obtained assuming that the lower levels of the subordinate transitions are excited from the ground state through photoexcitations due to the dilute stellar radiation field. In this case, the population ratio between the lower level and the ground state is approximately given by

$$\frac{N_2}{N_1} = \frac{g_2}{g_1}\frac{\beta_{12}^*}{\beta_{12}}\left[\exp\left(\frac{h\nu_{12}}{kT_*}\right) - 1\right]^{-1} , \qquad (8)$$

where the g_i's are the statistical weights, β_{12} is the photon escape probability (within the Sobolev approximation), β_{12}^* is the probability that a photon emitted at a given point hits the star surface, and T_* is the effective temperature of the star. For an effective temperature of 43000°K, the case of NGC 6543, the above ratio is of the order of (or less than) 10^{-3}, which is a rather small value.

Considering first only the resonance transitions,



'ig. 4. *IUE* SWP spectrum of NGC 6543. P-Cygni profiles of the resonance transitions of N V λ1240, C IV λ1549, and Si IV λ1396 are learly seen, as well as the subordinate transitions of O IV λ1341, O V λ1371, and N IV λ1718.

quation (7) allows us to estimate the product $(X_{ion}\dot{M})$ or each ion.If the ionization mechanism is collisional, hen the ionization degree of a given ion is a function of he electron temperature T_e only. Then, a plot of $\dot{M}$ gainst T_e can, in principle, define a region in the $(\dot{M}$, $_e)$ plane, from which we can estimate a pair of values atisfying the data (see Figure 5). It results in a mass-loss ate of 1.6×10^{-10} $M_\odot$ yr^{-1} and an electron temperaure for the wind of about 1.3×10^5 °K. It is impossible o reconcile this result with that obtained from the nalysis of the subordinate lines unless we assume that he ground level is excited by a diffuse radiation field roduced by a thick wind in the Lyman continuum at hat temperature. Or course this assumption introduces ome difficulties when explaining the ionization of the urrounding nebula. If the star excitation temperature etween the Lyman continuum and the helium ionizaion edge is higher, namely $T_{exc} \cong 62000$°K, and if for hoton energies higher than 54.4 eV the star color emperature is only 31000 °K, then a more or less onsistent picture with a mass-loss rate of about $\times 10^{-10}$ $M_\odot$ yr^{-1} is obtained in the framework of a adiative ionization mechanism (the Si IV data is not onsistent with such a rate of mass-loss). In spite of hese actual difficulties, which still require a deeper nalysis of the physical processes causing the excitation f the ground level and the ionization of the wind, a nass-loss rate as high as 10^{-7} $M_\odot$ yr^{-1} seems to be xcluded for NGC 6543. A similar analysis for NGC 826 leads us to the same conclusions.

Thus the actual interpretation of the UV data of the entral stars of planetary nebulae implies rates in the ange of $10^{-9} - 10^{-10}$ $M_\odot$ yr^{-1} although we cannot stablish as yet the nature of the ionization mechanism operating in the wind, as opposed to the case of blue supergiants.

IV. MASS-LOSS FROM Be STARS

Mass-loss estimates for Be stars found in the literature vary by several orders of magnitude.

Marlborough (1969) considered an axi-symmetric envelope (a "flat disk") in which the recombination lines

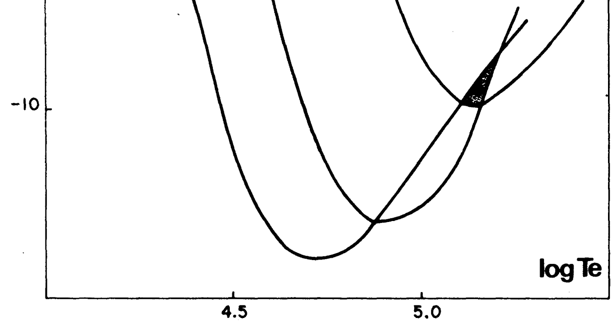


Fig. 5. Plot of $\dot{M}$ versus electron temperature for different observed lines in NGC 6543.

would be formed and he estimated rates of the order of 10^{-6} to 10^{-7} $M_\odot$ yr^{-1}. Hutchings (1970) considered that the recombination lines would be formed in a wind and from the fitting of the Hγ profile observed in γ Cas and κ Dra he obtained rates in the range $10^{-7} - 10^{-8}$ $M_\odot$ yr^{-1}.

Snow and Marlborough (1976) reported UV observations made with *Copernicus,* in which asymmetric profiles were observed in 59 Cyg, η Cen and ϕ Per. The blue-edge of the Si IV line indicated velocities of about 900 km s^{-1} and they estimated roughly the rate of mass-loss from 59 Cyg as being 10^{-10} $M_\odot$ yr^{-1}. Similarly, Burton and Evans (1976) obtained 2×10^{-11} $M_\odot$ yr^{-1} for η Cen.

We can notice immediately that there is a real discrepancy between the rates deduced from the Balmer lines and those deduced from the UV lines. We may speculate that they are not formed in the same place. The recombination lines would be formed in a denser region, near the equator, rotating around the star and with a small radial velocity; while the UV lines would be formed in an expanding envelope above and below such an equatorial disk.

The presence of such a "disk" is suggested by the following observations: (i) the correlation between the polarization and V sin i (Poeckert and Marlborough 1976); (ii) the anti-correlation between the standard deviation of the *V* magnitude with V sin i (Feinstein and Marraco 1979); and (iii) the correlation between the Hα line width with V sin i (Sletteback and Reynolds 1978).

Damineli and Pacheco (1981) from infrared and spectrophotometric observations made near the same epoch showed that there is a strong correlation between the infrared-excess and the Hα equivalent width. From the analysis of such data, they have concluded that if both continuum and line emission are originated in the "disk", then the average Hα optical depth perpendicular to the plane of such a "disk" is about 70, resulting in an average electron density of about 5×10^{11} cm^{-3}, in very good agreement with the value deduced from the polarimetric data (Poeckert and Marlborough 1976). In this case, the "average mass" of such a "disk" is about 7×10^{-9} $M_\odot$. On the other hand, the emission lines have a time scale for variability of several years. Assuming that the presence of the emission lines is associated with the presence of such a "disk", that the disappearance of the lines can be associated with the disappearance of the disk, and *also assuming that this mass is lost by the star,* then the corresponding average mass-loss rate is about 10^{-9} $M_\odot$ yr^{-1}.

Bruhweiler *et al.* (1978) have shown that the UV features appearing at λλ2061, 2068 and 2079 A in the spectrum of ϕ Per can be identified as transitions of Fe III originating from a metastable state (a^5S) with an energy of 5.01 eV above the ground level. They have also shown that the z^5p^0 state, which is common to both $a^5S - z^5p^0$ and $a^5D - z^5p^0$ multiplets, can be radiatively excited and then populates the a^5S state by radiative de-excitation. The observed features have asymmetric profiles, which can be interpreted as being formed in an expanding envelope. Since the relative populations of the metastable and the ground states are independent of the dilution factor, if the optical depth is small, a suitable estimate of the mass-loss rate can be done.

Recent *IUE* observations of π Aqr (Pacheco 1981) have revealed the presence of asymmetric Fe III lines originated from metastable states (Figure 6). The mass-loss rate can be estimated in this case from equation (7), correcting for the ratio between the metastable to the ground state population density. If most of the iron is Fe III, then the rate is about 2×10^{-9} $M_\odot$ yr^{-1}. For ϕ Per we obtained 1.5×10^{-9} $M_\odot$ yr^{-1}, re-analysing the data of Bruhweiler *et al.* (1978).

Therefore, a consistent picture for the mass-loss from Be stars is obtained with typical rates of about 10^{-9} $M_\odot$ yr^{-1}.

V. FINAL CONCLUSIONS

The different (hot) regions of the HR diagram in which we have reviewed the mass-loss diagnosis allow us to conclude that the rates are correlated with the luminosity of the star. The supergiants and Of stars have values in the range $10^{-6} - 10^{-5}$ $M_\odot$ yr^{-1}, the Be stars have typical rates of about 10^{-9} $M_\odot$ yr^{-1}, and the central stars of planetary nebulae, probably one order of magnitude smaller.

The rates estimated from the continuum and the recombination lines still have uncertainties within a factor of two, while the errors from the UV data are probably larger due to our ignorance of the ionization mechanisms.

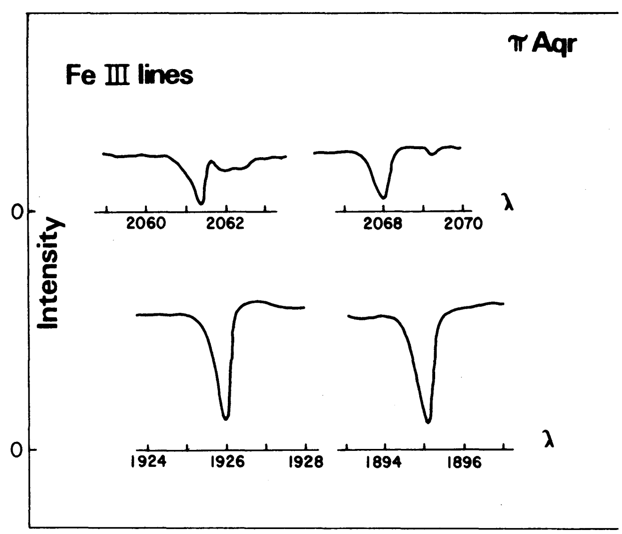


Fig. 6. Asymmetric Fe III lines in the UV spectrum of π Aqr originated from metastable states.

We did not analyse here the consequences of the ossible existence of an inner hot corona, which besides ıe physical influence in the ionization balance can be n important factor in providing the initial thrust to the ʼind.

Certainly, a large amount of hard work must be done efore we can say that all the mass-loss rates quoted may e considered trustworthy.

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DISCUSSION

Costero: ¿Qué tipos espectrales tienen en el visible los núcleos de planetarias que usted estudió? ¿Específicamente, a qué clase de luminosidad pertenecen?
Pacheco: Muestran espectro continuo y tienen luminosidades del orden de 1000 $L_\odot$.
Peimbert: ¿Se han obtenido tasas de pérdida de masa para otras nebulosas planetarias, además de NGC 6543 e IC 418?
Pacheco: Otros objetos han mostrado indicios de pérdida de masa. De nuestra muestra sólo los referidos tienen un número suficiente de líneas para un análisis completo de la pérdida de masa.
Mirabel: ¿Podría comentar sobre la relación entre los fuertes vientos estelares en estrellas de tipo temprano y la existencia de "burbujas" de gas caliente en el medio interestelar?
Pacheco: Apenas que tales efectos son mucho más sensibles para objetos inmersos en glóbulos de gas, como es el caso de HD 87643.

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