DECELERATION ZONES IN THE WINDS OF WR AND P CYGNI TYPE STARS

TIIT NUGIS
W.Struve Astrophysical Observatory of Tartu
202444 Tõravere
Estonia, USSR

ABSTRACT. Specific features both of continua and of line spectra of WR and P Cygni type stars can probably be explained if an extensive deceleration zone is proposed to exist in their stellar winds. The outflowing matter is first accelerated near the stellar surface, then follows the deceleration of the flow and after that the final acceleration of the outflowing matter takes place (i.e. the wind has an ADA–structure: acceleration–deceleration–acceleration). Such a structure of the wind probably arises due to the multiscattering of photons in the envelope having two detached shells, which are optically thick in resonance lines (these shells can form if ionization stratification is present in the envelope).

1. Observational evidence

The stellar wind theory and in most cases also the modelling of line spectra and continua of hot stars allow to conclude that the velocity of the outflowing matter increases with the distance from the stellar surface until an asymptotic regime of expansion with a constant velocity $v = v_\infty$ is achieved.

In the case of some types of hot stars it was concluded that a deceleration zone must be present in the wind.

For P Cygni the presence of a deceleration zone in the wind was proposed already by Kuan and Kuhi (1975) from the analysis of HI line profiles. But the analysis of HeI by Oegerle and Van Blerkom (1976) and also of HI performed by some other astronomers (e.g. Kunasz and Van Blerkom 1978) showed that an agreement with line profiles can be obtained by a monotonically increasing velocity run in the envelope.

The analysis of the continuous spectral energy distribution in IR and radio wavelengths and also the study of HI line profiles which was presented in the papers of Nugis et al. (1979a, b), showed that a deceleration zone must be present in the wind. In these papers the ADA–structure (acceleration–deceleration–acceleration) was proposed for the wind of P Cygni. In the study of Waters and Wasselius (1986) the long–wavelength spectral energy distribution was analyzed too. They concluded that an agreement with observations can be obtained with a monotoni-

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cally increasing $v(r)$ only on the assumption that the $60\mu m$ flux is caused mainly by circumstellar dust. The second possibility suggested by them is that in the interval $15R_* < r < 50R_*$ there is a stationary shell with the density exceeding about 5 times the density of the wind. These explanations seem to be too artificial.

In the case of WR stars the presence of a deceleration zone in their winds was found by Nugis (1984, 1990). Here also the wind seem to have the ADA–structure as well.

Using new observational information about P Cygni and WR winds our recent study confirms the previous results (Nugis, 1990).

One of the main observational facts pointing to the deceleration zone in the WR winds is the presence of quite broad absorption components of HeI lines. HeI lines cannot arise close to the stellar surface because helium is doubly ionized there. The velocity change, taking place far from the stellar surface in a non–deceleratingly expanding envelope, cannot cause broad absorption components, because the velocity, corresponding to the long–wavelength edge of the HeI absorption component, is less than the velocity derived from line widths of subordinate lines of high–IP ions, which can arise only quite close to the stellar surface (e.g. $\lambda 4945(NV)$ in the case of WN 5–6 stars). The width of HeI absorption components cannot be explained by local broadening mechanisms. This follows from the estimates for known broadening mechanisms and also from the fact that otherwise (when local broadening takes place) narrow absorption components should be present in many weak lines because absorption in the centre of the local line profiles is much stronger than in far wings. The question about the presence of macroturbulence in the envelopes of WR stars remains open, but neither macroturbulence nor microturbulence can explain the run of the spectral energy distribution in the IR spectral region. At first glance one can conclude from qualitative considerations that the spectral energy run in the IR spectral region of WR stars points to the envelope structure with a constant velocity run or, in some cases, even to the acceleration of the matter flow. This can be concluded only when assuming a homogeneous ionization structure. If the actual ionization structure is taken into account, then due to the fact that IR fluxes are effectively formed in that part of the envelope where helium changes from HeIII to HeII, matter density should decrease with radius more slowly than for a $v = const$ regime (that is, the deceleration zone must be present). The ratio of IR and radio fluxes of WR stars indicates that quite far from the stellar surface ($r \geq 50R_*$) a substantial acceleration of the matter flow takes place.

The presense of the ADA–structure in the P Cygni wind can most easily be proved by the analysis of the spectral energy run in the IR spectral region.

In the case of P Cygni variable narrow displaced absorption components in the profiles of many strong lines have been observed (Kolka 1983; Lamers et al. 1985). Quite strong radio–flux variations have also been detected (van den Oord et al. 1985). These are probably due to the change in the kinematic structure of the envelope, and cannot be explained by variations of the mass loss rate because emission lines and IR–fluxes do not undergo substantial changes. In the studies of Waters and Wesselius (1986) and Felli et al. (1985), it was proposed that strong radio–flux variations are caused by the lowering of ionization state in the radio emission region, i.e. hydrogen was proposed to become neutral from time to time. According to our study this explanation cannot be adopted because hydrogen cannot become neutral in the region where radio–fluxes are effectively formed. Although the optical depth in the principal series continuum of HI becomes quite high ($t_1 \approx 20 - 25$) already close to the stellar surface, hydrogen is kept ionized by photoionizations from excited states. Hydrogen becomes neutral only at distances $r \geq 3000 R_*$, i.e., at much larger distances as compared to the effective radio–flux formation region.

It must be said that in the paper by Lamers et al. (1985) it was alledged that small velocity shifts of absorption components of resonance lines of FeII in the UV spectrum of P Cygni exclude the possibility of the existence of the second acceleration zone. We made some estimates and found that if iron would be singly ionized in the interval $25R_* \leq r \leq 75R_*$, then we must observe high velocities of absorption components of FeII resonance lines. Actually we found that iron is in that region predominatingly doubly ionized and due to low T_e remains chiefly in the ground state. Therefore, the ADA–structure of the P Cygni envelope is not in conflict with low edge velocities of resonance FeII absorptions and of FeIII lines arising from metastable states. High velocities of the absorptions of some resonance lines of low–IP ions found from the IUE spectrum of P Cygni by Luud and Sapar (1980) confirm the presence of the ADA–structure. The maximum edge velocities of resonance absorptions found by Luud and Sapar (1980) tend to be $\approx 500 km/s$ just as follows from our models if the mean value of $7mJy$ is adopted for the radio–flux at 6cm.

In our previous study of P Cygni (Nugis et al. 1979 a, b), we tried to explain by high expansion velocity also the presence of broad wings of H_α and H_β lines. However, it was shown by the calculations of Kolka (1980),that these wings are partly due to expansion and partly due to electron scattering, therefore a somewhat lower asymptotic velocity v_∞, as compared to the study of the ADA–models of Nugis et al. (1979 a, b), seems to be quite justified. The higher radio–flux value used in our previous study seems to correspond to the phase of the minimum v_∞.

2. A possible mechanism

Gravitation cannot cause the deceleration of the matter flow in the winds of WR and P Cygni stars.

We propose that the mechanism, which causes the formation of the deceleration zone and of the ADA–structure, is the multiscattering of photons between two different detached regions (shells) of an envelope, which are optically thick in resonance lines (Fig.1). Such detached shells can probably exist, if ionization stratification is present in the wind and resonance lines of non–abundant elements are optically thick at large distances from the star. These conditions are probably satisfied in the case of WR and P Cygni stars.

The multiscattering of resonance photons between two shells causes the deceleration of the inner shell and acceleration of the outer shell, whereas the multiscattering of photons between the opposite sides of the outer shell contributes to an additional acceleration of that shell. The latter process is identical to the mechanism of Panagia and Macchetto, 1982. In their model, instead of the inner shell, there is a star itself and all the photons, which hit the star after being backscattered, would be thermalized and are therefore removed from the process. This strongly suppresses the effectiveness of the multiscattering process (especially near the stellar surface).

In the case of our two–shell model, the photons which hit the inner shell, are not thermalized. They will be backscattered and continue the process of multiscattering until they either acquire such a frequency that no resonance transition can absorb them (these quanta escape from the envelope or from the multiscattering region) or the photons will be destroyed.

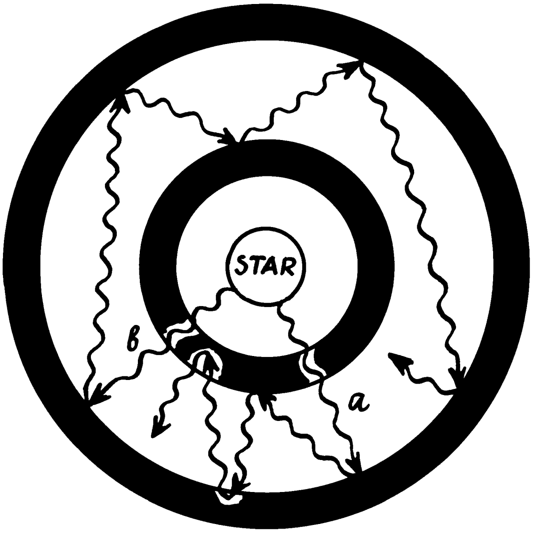

Fig. 1. A schematic representation of the mechanism of the multiscattering of photons between two shells, which are optically thick in resonance lines ((a) and (b) – two travelling photons, which are taking part in the multiscattering process).

Of course, the effectiveness of the multiscattering of resonance photons in the winds of hot stars needs further investigation. Abbott and Lucy (1985) and Friend and Castor (1983) concluded that multiscattering takes place in the stellar winds of OB stars, but that it is not so effective in accelerating the wind as proposed by simple estimates of Panagia and Macchetto (1982). A detailed investigation of this mechanism is needed for hot stars. In the case of OB stars probably some multiscattering of resonance photons between different shells may also take place. This may explain the formation of narrow displaced absorption components seen in some strong resonance lines.

References

Abbott, D.C. and Lucy, L.B. 1985. *Astrophys. J.*, **288**, 679.
Felli, M., Stanga, R., Oliva, E. and Panagia, N., 1985. *Astr. Astrophys.*, **151**, 27.
Friend, D.B. and Castor, J.I., 1983. *Astrophys. J.*, **272**, 259.
Kolka, I., 1980. *ENSV TA Preprint* A–4.
Kolka, I., 1983. *ENSV TA Toimetised. Füüs. Matem.* Vol. 32, 51.
Kuan, P. and Kuhi, L.V., 1975. *Astrophys. J.*, **199**, 148.
Kunasz, P. and Van Blerkom, D., 1978. *Astrophys. J.*, **224**, 193.

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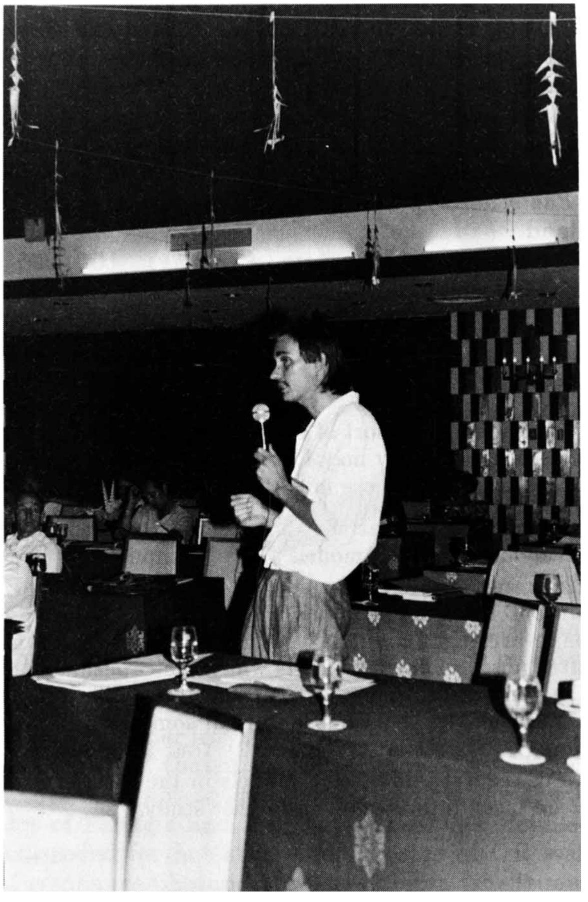
Lamers, H.J.G.L.M., Korevaar, P. and Cassatella, A., 1985. *Astr. Astrophys.*, **149**, 28.
Luud, L. and Sapar, A., 1980. *Tartu Astrofüüs. Obs. Teated*, No 60, 3.
Nugis, T., 1984. *Tartu Astrofüüs. Obs. Publ.*, **50**, 101.
Nugis, T., 1990. *Astrofiz.*, **32**, 85.
Nugis, T., Kolka. I. and Luud, L., 1979a. *Mass Loss and Evolution of O-Type Stars, IAU Symp.* No 87, p.39, eds Conti, P.S. & de Loore, C.W.H., Reidel, Dordrecht, Holland.
Nugis, T., Kolka, I. and Luud, L., 1979b. *Tartu Astrofüüs. Obs. Publ.*, **47**, 191.
Oegerle, W.R. and Van Blerkom, D., 1978. *Astrophys. J.*, **224**, 193.
Van den Oord, G.H.J., Waters, L.B.F.M., Abbott, D.C., Bieging, J.H. and Churchwell, E., 1985. *Radio Stars*, p.111, eds Hjellming, R.M. & Gibson, D.M., Reidel, Dordrecht, Holland.
Panagia, N. and Macchetto, F., 1982. *Astr. Astrophys.*, **106**, 266.
Waters, L.B.F.H. and Wesselius, P.R., 1986. *Astr. Astrophys.*, **155**, 104.

DISCUSSION

Cherepashchuk: In your model some sort of Rayleigh-Taylor instability must be present in the acceleration zone. This instability may form the blobs.
Nugis: Yes, I think that such a structure must be unstable.

Owocki: (1) I do not understand what specific observations require you to invoke deceleration zones. (2) In dynamical wind models I have computed, it is easy to obtain such deceleration zones if parameters are chosen so that $\dot{M} \gtrsim \dot{M}_{CAK}$.
Nugis: (1) The main observational facts which point to the presence of deceleration are the shapes of the long wavelength continua and in the case of some types of WR stars the wide *HeI* violet shifted absorption components which indicate that the expansion velocity at some place in the zone of formation of *HeI* lines must be less than the expansion velocity of the region, where the subordinate lines of some high IP lines are formed (the latter are formed closer to the stellar surface). (2) Your information about the presence of deceleration zones in the dynamical wind models in the case when $\dot{M} \gtrsim \dot{M}_{CAK}$ is very important and must be taken into account in further study.



Werner Schmutz

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