THE WIND OF P CYGNI

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The stationary features of the wind of P Cygni are considerably different from those of 'normal' supergiant winds with comparable luminosity. In contrast to such winds, which are generally accepted to be driven by radiation pressure, P Cygni's mass-loss rate is higher by a factor of 5, the terminal velocity is higher by a factor of 10, and the velocity law itself is much flatter than would be expected from a first glance at glance at typical scaling relations. However, these relations depend crucially and non-linearly on the star's distance from the Eddington limit, which for P Cyg is very small (see below). Here we investigate whether the acceleration mechanism of P Cygni's wind can also be explained by line pressure and to what extent self-consistent wind models represent the observed quantities (especially the IR energy distribution).

Stellar and wind parameters: The stellar parameters of P Cyg are fairly well known from an investigation by Lamers *et al.* (1983). Assuming $E(B-V) = 0.63 \pm 0.05$, they found $T_{eff} = (19300 \pm 2000)$ K, $R_* = (76 \pm 15)\,R_\odot$, $d = (1.8 \pm 0.1)$ kpc. According to the evolutionary tracks of Maeder and Meynet (1987), P Cyg is on its way back from the RGB with a mass of $23.5\,(+18,-9)\,M_\odot$, which results in $\log(g) = 2.05 \pm 0.25$ and $L/L_{Edd} = 0.73$.

The wind's terminal velocity is more uncertain. Cassatella *et al.* (1979) found a value of 300 km/s from the Mg II, Fe II lines, whereas Lamers *et al.* (1985) argued that the blue absorption edges are contaminated by turbulent motion, and that the true terminal velocity is 206 km/s.

The usual way to determine mass-loss rates is by the use of radio data. P Cygni is extremely well observed from 0.33 to 20 cm (Wendker 1987). A compilation of these data leads to a high correlation with the thermal emission model, from which we find (assuming $d = 1.8 \pm 0.1$ kpc): $\dot{M}(10^{-6} M_\odot/yr)/v_\infty(km/s) = 4.177\,(+1.45,-1.07) \times 10^{-2}$. A more difficult problem is the determination of the velocity law. Using the ground-based IR fluxes by Abbot *et al.* (1984, 0.98--20 μm) and the IRAS fluxes (20--100 μm), Waters *et al.* (1986) argued that the best fit could be obtained by a *linear* velocity law $v(r) = v_\infty\{0.1 + 0.057(r/R_* - 1)\}$, where the fluxes at 60 and 100 cm are due to enhanced emission by dust or originate from a shell at about $15\,R_*$. *This fit, however, is not unique.* A typical β-velocity law -- excluded by Waters *et al.* -- with $\beta = 4$ and a much smaller initial velocity ($v_0 = 4 \times 10^{-4}\,v_\infty$) reproduces the observed IR flux and the IR excess as well; both the linear and the $\beta = 4$ laws show the same density structure in the IR-emitting region.

The acceleration: The first quantitative analysis of the acceleration mechanism was carried out by Lamers (1986). On the basis of the linear velocity law he showed that neither turbulent pressure, nor dissipating sound waves, nor pure continuum pressure are able to provide sufficient acceleration to drive P Cygni's wind. He concluded that the acceleration must be due to line radiation pressure, probably by a large number of

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optically thin lines in the Balmer continuum. Simple algebra, however, shows that the radiative acceleration necessary to yield the linear velocity law should be due to optically thin lines only in the lower part of the wind ($r < 3R_*$, $v < 0.22 v_\infty$), whereas the outer part of the wind must be accelerated only by optically thick lines. In order to test these constraints, we calculated the line force for the linear velocity field, by applying the NLTE code of Pauldrach (1987) for the parameters of P Cyg. We found that the linear velocity law gives rise to an acceleration both by optically thick and optically thin lines (in ratio 0.61) throughout the wind, which is in strong contradiction to the applied input and shows that a linear velocity law cannot be obtained by radiative acceleration in the case of P Cygni. For the β-velocity law, however, the situation looks much better. The resulting NLTE line force (including line overlap, *cf.* Puls 1987) turns out to be nearly identical to that necessary for building up the β-law. Hence it is most probable that the acceleration mechanism is line pressure, resulting in a velocity field with the typical β-structure of radiatively driven winds, giving the IR excess.

Radiatively driven wind models: In order to examine how far self-consistent wind models are able to reproduce the observed features, we proceeded in two steps. First we calculated a stellar wind model with the given force-multiplier parameters $k = 0.088$, $\alpha = 0.524$, $\delta = 0.059$, and $\log(g) = 2.04$, resulting in $\dot{M} = 12.1 \times 10^{-6}\, M_\odot/yr$, $v_\infty = 213$ km/s, values that lie exactly in the expected region for P Cyg. *The observed IR excess was also reproduced.* The second step was (and is) the calculation of completely self-consistent models, including the simultaneous solution of hydrodynamics, NLTE rate equations and radiation transport with line overlap. This last topic is especially important for quantitative results, since the line overlap (strong line blocking) leads to a significant reduction of the line force. From the three tracks calculated by Pauldrach et al. (1988) we choose the $R = 76\, R_\odot$ track since this is the most probable radius from our investigation of IR and radio data. Up to now we have finished only our calculations for a model with $\log(g) = 2.0$, corresponding to model 3 by Pauldrach, on the upper track of the mass-loss function. Comparing our results to the results of the single-line approximation by Pauldrach, we find a reduction of both mass-loss rate and terminal velocity in the expected direction:

$\dot{M}/(10^{-6} M_\odot/yr)$ = 32 (single-line approx.) or 21 (with line overlap);
$v_\infty/(km/s)$ = 280 (single-line) or 228 (line overlap);
$10^7\, \dot{M}/v_\infty$ = 1.17 (single-line) or 0.9 (line overlap).

Future work: The next steps in our fully self-consistent description of the wind of P Cygni, underway at present, are the calculation of a model grid around the discontinuity in the mass-loss function (see Pauldrach et al.) and the investigation of the ionization balance of metals (especially Fe II, III) in comparison to observations. From the work presented here, however, it is evident that the stationary features of P Cygni's wind can be explained with radiation pressure as the dominant acceleration mechanism, with stellar parameters $T_{eff} \approx 19300$ K, $\log(g) \approx 2.04$, $R_* \approx 76\, R_\odot$, *yielding a mass of* $\underline{23\, M_\odot}$.

References: Abbott, Telesco, & Wolff 1984, *Astrophys.J.* **279**, 225; Cassatella *et al.* 1979, *Astron.Astrophys.* **79**, 223; Lamers, de Groot, & Cassatella 1983, *Astron. Astrophys.* **128**, 299; Lamers, Korevaar, & Cassatella 1985, *Astron.Astrophys.* **149**, 29; Lamers 1986, *Astron.Astrophys.* **159**, 90; Maeder & Meynet 1987, *Astron.Astrophys.* **182**, 243; Pauldrach 1987, *Astron.Astrophys.* **183**, 295; Pauldrach, Puls, & Kudritzki 1988, these proceedings; Puls 1987, *Astron.Astrophys.* **184**, 227; Waters & Wesselius 1986, *Astron.Astrophys.* **155**, 104; Wendker 1987, *Astron.Astrophys.Suppl.* **69**, 87.